SIO REFERENCE SERIES

CLANDESTINE METHODS FOR THE DETERMINATION OF BEACH TRAFFICABILITY

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Chapter 1
Introduction

1.1 General.

Naval Special Warfare (NSW) units are assigned the mission of conducting reconnaissance of landing beaches in support of amphibious operations. This mission includes the determination of beach composition and trafficability available to various vehicles as they transit the beach and pass through beach exits.

This report describes modern techniques, developed from soil mechanics, for determining beach trafficability. These techniques, compared to current NSW methods, require less training and shorter swimmer exposure times, and allow for a more simplified sampling, yet derive a more quantitative trafficability estimate with more repeatable results. This report recommends that these new measurement techniques be incorporated into NSW doctrine.

Remote Sensors ~~methods~~ for determining beach trafficability are also identified and addressed. While these methods are outside of NSW assets, they are valuable for the purpose of identifying candidate beaches before committing NSW personnel for final verification. Keywords: Computations; aerial photographs.

1.2 Summary.

Two basic approaches to assessment of beach trafficability are available. The first of the approaches requires observations by a swimmer/diver pair during a clandestine hydrographic reconnaissance. These observations are relatively few and deduce trafficability from either a bottom sample or SUROBS under the breakpoint, or by geotechnical measurements with a relatively small diver test (MSPT). The second basic approach relies either upon interpretation of aerial photos or upon an air delivered sensors such as the aerial penetrometer and multispectral scanner (MSS).

Swimmer/diver observations will give the most accurate assessment of beach trafficability because the observation points can be precisely confined to the breakpoint. Among the possible techniques for making these observations, the geotechnical diver tool (MSPT) will give the greatest accuracy. This results from measuring directly the existing soil structure of the beach without disruption to natural beach packing and fabric. The MSPT is adaptable to any beach regardless of the presence or absence of waves and tides. It can also be used in at least its static mode to directly measure soil strength in the beach exits.

If the swimmer burdens or available space on insertion vehicles will not permit use of the MSPT, then indirect methods from swimmer/diver observations will provide the next most reliable assessment of beach trafficability. Taking a bottom sample and returning it to the insertion platform for grain size analysis gives the greatest accuracy among these indirect methods. Inferring trafficability from SUROBS involves an additional set of uncertainties in the wave statistics to grain size analysis, but is the most time efficient, unburdened indirect approach by swimmers.

Interpretation of aerial and satellite photographs is best suited for beach feasibility studies, where a "go-or-no-go" assessment of trafficability must be determined among a large number of candidate beaches, possibly spread over a large geographic region. The results are approximate primarily due to uncertainties in determination of mean foreshore widths and slopes. Either of these parameters can give a beach trafficability estimate, but only when a tidal variation in sea level is present and known. Aerial photos also provide extensive qualitative information about beach exits, particularly foilage, debris and other obstructions which are not related to soils strength.

Reflectance data from airborne or satellite based multispectral scanners (MSS) can also be utilized for beach feasability studies. This method requires knowledge of the minerology of the beach composition which can be obtained from geologic maps or the MSS itself. Grain sizes are calculated based upon the relative distribution of 17 spectral bands, and from these the trafficability can be estimated. The method suffers at this time from ground truthing based primarily upon laboratory measurements, although limited verification from aircraft data has been achieved for Lake Michigan.

Once candidate beaches are identified from aerial photos or MSS data, follow-up verification by more accurate methods is justified. The aerial penetrometer may be an attractive low-cost alternative to swimmer/diver insertion in relatively remote areas lacking sophisticated coastal air defenses. However, the results of the aerial penetrometer must be regarded as less reliable than trafficability estimates from swimmer/diver observations. This is largely due to the lack of control in dropping the aerial penetrometer on the beach foreshore with wind drift and pilot error.

Chapter 2
Principles of Trafficability

2.1 General.

Trafficability is the ability of a soil to support the movement of vehicles. The particular soils in question include beach materials extending in the nearshore from the point of grounding of landing craft to the beach exits at the backshore or first line of vegetation.

Trafficability is a function of soil strength as determined by the bearing capacity and shearing strength of the soil surface and sub-surface. The bearing capacity must be sufficient to support the weight of the vehicle, while the shearing strength must be adequate to permit the vehicle to develop enough traction to provide the forward thrust necessary to overcome both the beach gradient and rolling resistance.

Soil strength will vary with soil depth, composition, moisture content, and the number of vehicle passes. Generally soil strength increases with increasing penetration into the soil mass. The critical soil depth for trafficability, or "critical layer," will vary somewhat with vehicle type and weight, but is normally considered to be the soil layer from 6 to 12 inches below the surface. The most important aspect of beach composition affecting soil strength is the grain size of the granular material comprising the critical layer. The grain size will vary with both soil depth and on/off shore position due to shear sorting by waves. The types of grains, whether minerals or shell fragments, is of secondary importance. The accumulation of moisture may increase or decrease soil strength depending upon composition. Therefore, separate consideration should be given to the wet and dry portion of the beach as well as to rainfall and tidal range. Similarly, the strength of a soil may increase or decrease when subjected to traffic with subsequent working of the soil. Hence, "virgin trafficability" should be considered distinct from "multi-pass trafficability." This distinction is accounted for physically by a property called "remolding." The remolding index (or ratio of measured strength after traffic to the original strength) defines the change in strength due to repeated traffic on a soil area.

2.2 Measurements.

A determination of bearing and traction capacities of a soil require some sort of measurement of mass shearing resistance. Up to and including the period of WWII the standard engineering methods for making an in situ determination of shearing resistance included the "Sub-grade Modulus" method, the "California Bearing Ratio" and the "North Dakota Cone Bearing" method. These methods all involved complex and heavy apparatus, some excavation test pits, and the expenditure of relatively large amounts of mechanical energy and observation time. Therefore, the UDT was forced to assess trafficability without the aid of any geotechnical measurements. This was, and still is, accomplished by a subjective determination of trafficability based upon thrusting a man's fist or foot into the wet and dry portions of the beach face. Trafficability was then judged "excellent," "good," "fair," "poor," or "bad" for 2-wheel drive, 4-wheel drive, and tracked vehicles, plus personnel (Reference (1), Appendix C). Besides requiring a well trained individual, this "human penetrometer" method is subject to the following limitations:

- The man must previously be trained for a wide range of possible grain size distributions.
- The man fails to assess soil strength at the critical layer. Surface firmness can be quite different from that of the critical layer if wave action has recently modified the beach.
- The kind of information gathered does not permit determination of remolding indices or multi-pass trafficability.
- The kind of information gathered does not permit assessment of soil strength for conditions other than those which prevailed the day of the observation. In particular, estimates of trafficability following a heavy rain or high tide are not possible.

- The man's accuracy could be altered by mission stress, hypothermia, and by wounds.

Of course, the primary advantage of the "human penetrometer" is that the method requires no additional equipment to encumber the mission.

An alternative method dating back to WWII is a qualitative assessment of beach trafficability based upon a compositional analysis of "grab samples" of beach material. The principal limitation with this method has been the lack of a physically based "criteria" defining where and how many of these samples should be taken to sufficiently generalize the trafficability of an entire beach. A criteria to apply this method to equilibrium beaches under clandestine situations is developed in sections 3.1 and 3.2 of this work.

Since WWII, the engineering methods for measuring mass shearing resistance of the critical layer have been greatly simplified with the advent of the cone penetrometer. Although a great variety of cone penetrometers are in use today, they all express shearing resistance in terms of a "cone index" number which will be used throughout this report. The cone index is the resistance to penetration into the soil of a 30^{o} cone as expressed in pounds per square inch. The great wealth of vehicle mobility data gathered during WWII and expressed in terms of the then standard engineering strength values of California Bearing ratio, unconfined compressive strength or North Dakota bearing index may be expressed in terms of the cone index using the calibration curves shown in Figure 2-1. Certain cone penetrometers are based upon a dynamic method, measuring shearing resistance in terms of the number of blows required to penetrate fixed increments of depth. These data can be converted to an average cone index at each depth increment per each blow using the calibration curve given in Figure 2-2.

The cone index gives a quantitative measure of straight line virgin trafficability. For the purposes of assessing multi-pass trafficability, the cone index number is multiplied by the remolding index to yield the "rating cone index" (RCI). The RCI is the parameter on which consideration for trafficability should be based during such assault landings as is shown in Figure 2-3. A large number of post-WWII studies have correlated soil strength with trafficability requirements of ground and assault vehicles (References 2, 3, 4, 5, 6, 7). Based upon these findings Table 2-1, a condensed classification of vehicle multi-pass trafficability, has been compiled according to the range of rating cone index (RCI) that will support 50 straight passes of a given vehicle type or one vehicle executing severe maneuvers without becoming immobilized. These same values are roughly equivalent to virgin trafficability when severe vehicle maneuvers are required (Reference 6).

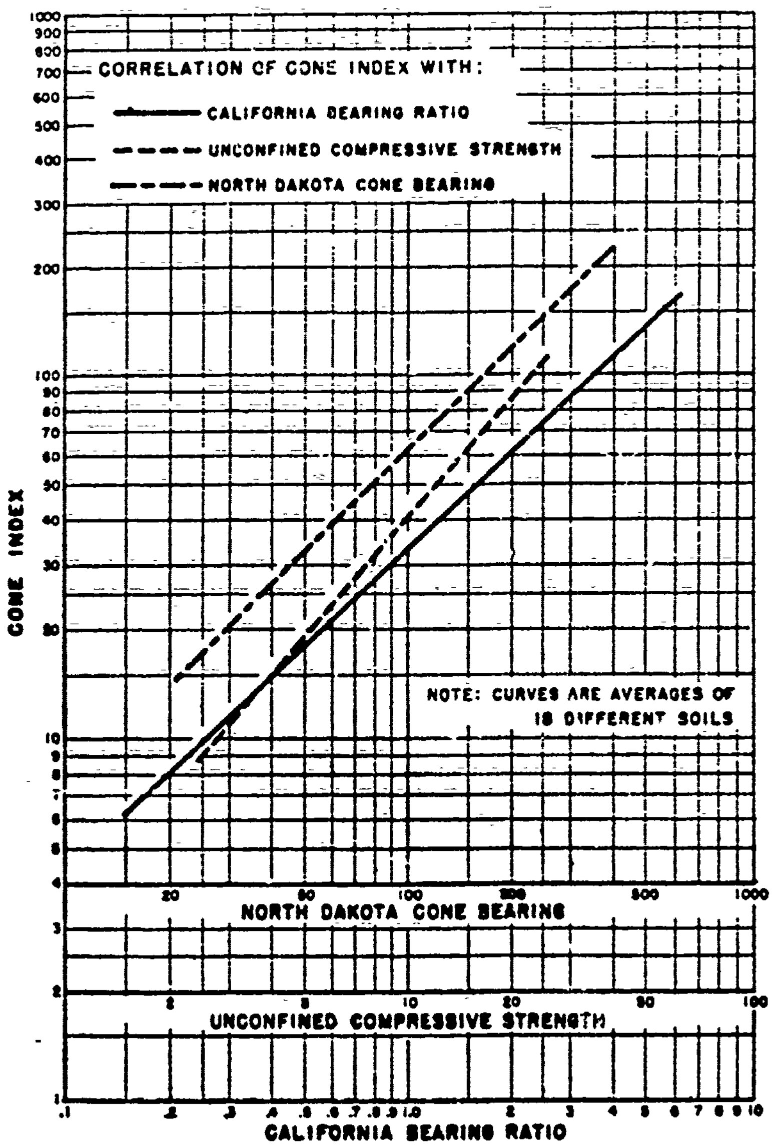


Figure 2-1 Relation of cone index to standard engineering soil strength values of California Bearing Ratio, unconfined compressive strength and North Dakota cone bearing.

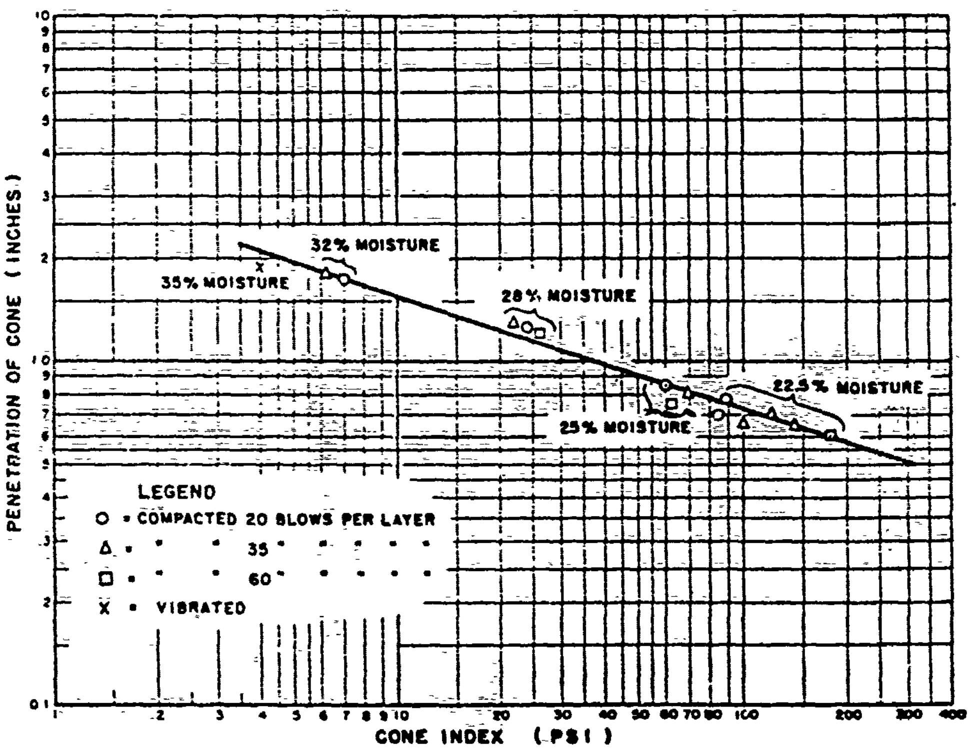


Figure 2-2 Typical relationship of cone index with depth of penetration and moisture content occuring at various stages of laboratory remolding

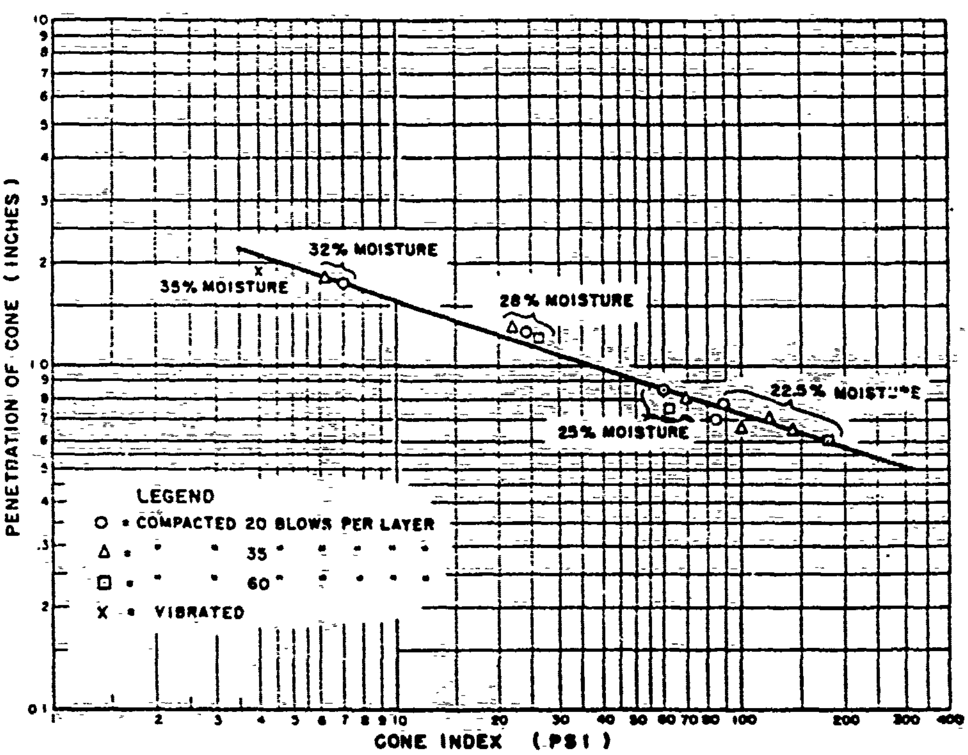


Figure 2-2 Typical relationship of cone index with depth of penetration and moisture content occuring at various stages of laboratory remolding

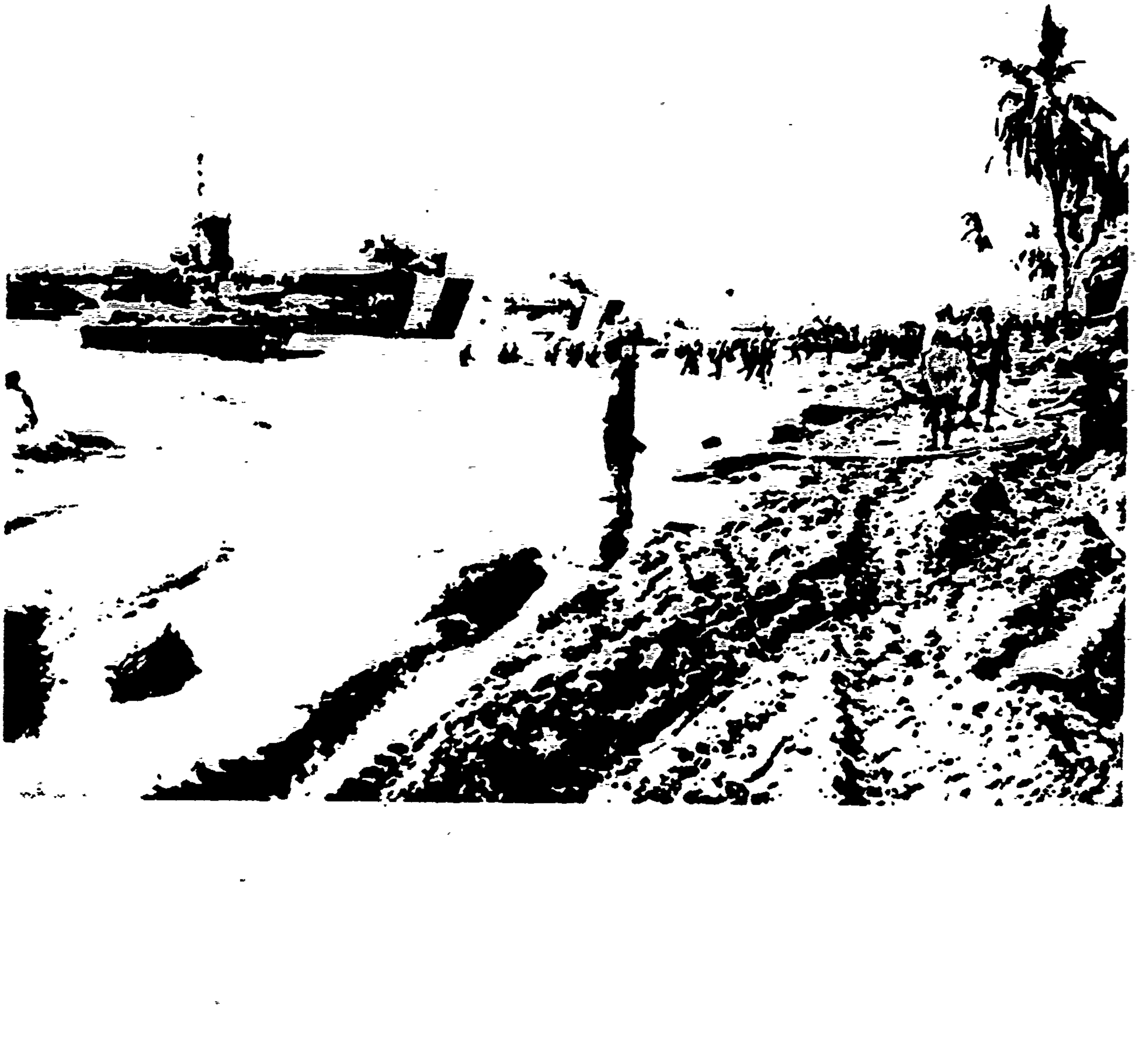


Figure 2-3 Examples of disruption of the backshore due to multi-pass traffic at Guam, 1944

Table 2-1

Classification of Vehicle Multi-Pass Trafficability

Category	RCI Range (PSI)	Vehicle Type
1	20 - 29	M29C weasel, M76 otter, snowmobile, all terrain cycles (ATC)
2	30 - 49	M-8A1 and M8A2 high-speed tractors, D-7 tractor and M-274 Mule
3	50 - 59	M151 series (4x4) Jeeps; M-4, M-6, M-8 (4x4) and (8x8) tractors; M-48 tank; M-101A1 Howitzer; LVT-P7 armored personnel carrier
4	60 - 69	M-60 tank, M-135 truck; LARC-5 (4x4) amphibious cargo carrier; M-34, M-49, M-50, M-59, M-60, M-108, M-109, M-275, M-561 (6x6) trucks; M-123A1, M-114 Howitzer
5	70 - 79	M-54 (6x6) truck; LARC-15 (4x4) amphibious cargo carrier; M-809, M-815, M-816, M-811 (6x6) trucks; XM198 Howitzer; M-1A1 155 mm gun
6	80 - 99	Rear-wheel drive trucks and trailed vehicles intended primarily for highway use, i.e., 4x2, 1/2 ton pick up trucks
7	100 or greater	Rear-wheel drive vehicles and others that generally are not expected to operate off roads, i.e., 4x2 5-ton dump truck

2.3 Beach and Shoreline Composition.

Soils composition of beach and shoreline structures may be divided into four general groups for evaluation of strength characteristics, especially when wet, for beach landing operations.

The first group consists of coarse-grained gravelly and sandy soils. Where these do not contain large amounts of silt or clay, they usually have fairly high strengths even when wet, and are most suitable for landing operations. These soils are most typical of the foreshore and backshore regions of beaches subjected to large waves.

The second group consists of the highly plastic clays, frequently called heavy or fat clays, gumbo, or buckshot. Their strengths are affected moderately by normal natural moisture changes, and are generally next in order of preference to sands and gravels. These soils are common to the nearshore regions of beaches situated near river deltas. The very existence of deltaic beach structures is evidence of low wave conditions found within marginal seas.

The third group in order of trafficability is clayey gravels and sands, and clays of low to medium plasticity. The percentage of clay determines their plasticity, with a clay content of 15 percent often used as the dividing line between plastic and nonplastic soils. These soils are found in the nearshore regions of tidal lagoons and estuaries fed by seasonal river flows.

Soils in the fourth group, least suitable for beach landings when wet, include lean clays and silts which may or may not have small amounts of gravel in them. Soils in this group include silt, diatomaceous soil, lean organic clay, organic silt, loam or till. The high strengths of these soils when dry are greatly reduced by the addition of comparatively small quantities of moisture. Peat, muck and swamp soils are not considered trafficable except by amphibious type vehicles. These soils are most typical of beaches formed along the banks of rivers that have little or no exposure to waves.

Table 2-2 summarizes these four soil groups according to their wet strength properties, including the probable ranges of remolding and rated cone indices.

Table 2-2

Trafficability as a Function of Beach Composition when Wet

Group	Soils	Probable Cone Index Range	Probable Remolding Index Range	Probable Rating Cone Index Range	Remarks
I	Coarse-grained cohesionless sands and gravels.	80-300	1	80-300	Will support continuous wheeled traffic with low pressure tires. Moist sands good, dry sands fair.
II	Inorganic clays of high plasticity, fat clays.	55-165	0.75 to 1.35	65-140	Will usually support more than 50 cycles of wheeled vehicles. Traction may be difficult at times.
III	Clayey gravels, gravel-sand-clay mixtures, clayey sands, sand-clay mixtures, gravelley clays, sandy clays, inorganic clays of low to medium plasticity, lean clays, silty clays.	85-175	0.45 to 0.75	45-125	Will usually support limited traffic of wheeled vehicles. Traction will be difficult in most cases.
IV	Silty gravels, gravel-sand-silt mixtures, silty sands, sand-silt mixtures, inorganic silts and very fine sands, rock flour, silty or clayey fine sands or clayey silts with slight plasticity, inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts, organic silts and organic silty clays of low plasticity, organic clays of medium to high plasticity.	85-180	0.25 to 0.85	25-120	Will usually not support more than a single pass. Traction will be difficult in most cases. Applies to class I-III vehicles.

2.4 Moisture Content.

The strength values presented in Table 2-2 are for saturated soils, i.e., those whose moisture content has reached 100% of the maximum soil storage capacity. To estimate moisture content M in inches on any given day, d + 1, after a particular observation, i, use the following equation (from Reference (7)):

$$M_{d+1} = M_d \left(\sum_{i=1}^{6} A' Y^i \right) \qquad \text{for } R_d < 0.10$$

$$M_{d+1} = M_d - 0.22\, R_d - 0.01 \qquad \text{for } (S_d + Z_d) > R_d \geq 0.10$$

$$M_{d+1} = M_d + (0.60)\, S_d - 0.02 \qquad \text{for } R_d \geq (S_d + Z_d)$$

where

$$Y_d = M_d - 0.61$$

$$\sum_{i=1}^{6} A' Y^i = (0.054)\, Y - (0.083)\, Y^2 + (3.057)\, Y^3 - (6.625)\, Y^4 + (5.069)\, Y^5 - (1.316)\, Y^6 \qquad \textbf{Eq. (1)}$$

d = day

R = rainfall (inches)

Z = available storage (inches) 0 to 6 inch layer

A' = parameter expansion coefficient

Y = moisture content of the critical layer 6 to 12 inches

S = available storage (inches) of the critical layer

Backing out the moisture content, M_{d+1}, from equation (1) allows calculations of dry trafficability from wet in terms of percentage of saturated wet strength, i.e., the ratio of strength at a given moisture content, M_{d+1}, to the saturated wet strength. These values are compiled in Table 2-3 (from Reference (7)).

For example, if a clay-sands beach had a saturated wet strength RCI of 15 psi according to Table 2-2, then the dry trafficability would correspond to a rated cone index in excess of 93.1 psi. This would be trafficable to most any vehicle when dry but not when wet.

Utilization of Table 2-3 must be regarded as approximate. It is based on a least squares fit to strength data derived from a wide range of soils (References (2) - (8)). Certain soil types may show errors as great as 50% in the percentage strength ratios given. In particular, dry sands will show a 50% increase in RCI between 1% and 0.5% moisture content by weight (less than 1.4 inches of absolute water content.)

Table 2-3

Percentage of Saturated Wet Strength
As a Function of Moisture Content

	Water Content Within the 6 to 12 inch layer (inches)	Saturated Wet Strength (%) Soil Group I	II	III & IV
DRY	1.40	46	112	621
	1.40	46	111	621
	1.50	40	111	463
	1.60	26	109	352
	1.65	46	108	274
	1.70	55	105	208
	1.75	77	100	163
	1.80	91	100	126
SATURATED	1.85	100	100	100
	1.90	95	85	81
	1.95	87	77	65
	2.00	61	62	53
FLUIDIZED	2.05	47	56	42

Chapter 3
Determination of Trafficability by Swimmers

3.1 General.

Observations gathered during a clandestine hydrographic reconnaissance may be used to infer beach trafficability. These may be accomplished by either unburdened surface swimmers in a night reconnaissance or by divers with breathing apparatus during a submerged reconnaissance. In either case bottom samples or SUROBS must be gathered from inside the surf zone. Here the grain size and beach slope are in steady state equilibrium with the wave stress. The wave stress is therefore the shearing reference standard. Beach material with shear strength less than the wave stress is quickly resuspended and advected away by nearshore currents. All remaining beach material is capable of supporting loads at least as large as the wave stress. The decisive question is how the wave stress compares to vehicle loads. Trafficability can be deduced based on this principle by either observing beach composition or wave heights and periods within the surf zone.

3.2 Trafficability from Qualitative Beach Composition.

A grab sample of bottom material is collected at points within the surf zone for each potential invasion lane. The on/off shore position of each sample point should be beneath the break point of the highest breaking waves. Here the depth of the water will be approximately 5/4 the breaker height. The number and long shore position of sample points depends upon the degree of three-dimensionality of the beach. A fully two-dimensional beach which is unbounded in both long shore directions with a uniform surf zone requires only one sample point in the center of the invasion land. A three-dimensional beach, e.g., concave, convex, exponential, bayside, baymouth, midbay bar, bayhead bar, tambolo, spit or pocket beach, requires one sample at each major charge in shoreline or bathemetric geometry. For example, a simple pocket beach requires a minimum of three sample points, on both flanks and in the center of the invasion lane. If the pocket beach has large cusps, then samples are required off the horns and in the center of each cusp.

At each sample point, the swimmer or diver should attempt to gather material from the critical layer depth, about 6 inches below the bottom level. He notes the qualitative composition from these depths in terms of class I-VI soils tabulated in Table 2-2 and enters his observation and location on a grease pencil slate. Later, Table 2-2 is used to designate the range in wet rated cone index (RCI) based on the qualitative composition observations at each location. The dry rated cone index on the foreshore and backshore is calculated from Table 3-3 by multiplying the wet RCI times the percentage of saturated wet strength according to the qualitative composition classification. The resulting wet and dry RCI values are then compared to Table 2-1 to determine vehicle trafficability under wet and dry conditions.

Advantages of this method are:

- No additional equipment required.
- Wet and dry trafficabilities accessible.
- Under average surf conditions (1 meter breaker heights) a reasonable estimate of trafficability is obtained from the forward grounding point of landing craft LCPLMK4, LCVP, LCM6, LCM8, LCM8-Aluminum, LCU class 1466, 1610, 1627 and 1646.
- Swimmer or diver is not required to leave the water.

Limitations of this method are:

- The estimate of trafficability is only known within a confidence interval based upon qualitative soils classification.
- Shoreward trafficability accuracy depends on an equilibrium beach profile. On equilibrium beaches, trafficability will improve shoreward of the breakpoint. The estimate is therefore a "worst case" corresponding to the neighborhood of the grounding point.

- Tables 2-2 and 2-3 are approximate based on average soils.

3.3 Trafficability from Quantitative Beach Composition.

The grab samples collected according to the above discussion are placed in Zip-lock plastic bags and returned to the insertion platform for subsequent grain size analysis. The only special equipment needed for this analysis is a fresh water filled tube or graduated column of known height. A fraction of the sample is poured into a graduated column filled with water. The time required for the sample of bottom material to settle to the bottom the column is measured with a stopwatch. The settling velocity of the sample is calculated by dividing the length of the graduated column by the time required for the sample to settle. The average grain size D is deduced from the settling velocity using the settling curve in water from Figure 3-1. If the beach slope, BETA, is known from the results of the hydrographic reconnaissance, then the cone index may be calculated using the following regression equation:

$$\text{CONE INDEX (PSI)} = \frac{2\sin(\Phi - B)}{\tan\Phi\,(1+\cos\Phi)}\left[(10240)D + \frac{0.0024}{D^2} - \frac{0.158}{D}\right] \quad \text{if } D \geq 10^{-1}\text{ mm}$$

$$= \frac{\sin(\Phi - B)}{\tan\Phi\,(1+\cos\Phi)}\left[\frac{0.0376 \times 10^{-6}}{0.6 \times D^3}\right]^{5/2} \quad \text{if } D < 10^{-1}\text{ mm} \qquad \text{Eq. (2)}$$

where D is average grain diameter in inches and Φ is the angle of internal friction which varies from 30° to 34° depending upon grain shape. Generally trafficability decreases with increasing beach slope, BETA, according to equation (2). Reduced trafficability is most pronounced at the sharp slope increase on the face of the berm or long shore bars. If the beach slope is not known, compute the cone index for a flat bottom according to:

$$\text{CONE INDEX (PSI)} = \frac{\sin \Phi}{\tan \Phi\,(1 + \cos \Phi)} \left[(10240)D + \frac{0.0024}{D^2} - \frac{0.158}{D}\right] \quad \text{if } D \geq 10^{-1}\ \text{mm}$$

$$= \frac{\sin \Phi}{\tan \Phi\,(1 + \cos \Phi)} \left[\frac{0.0376 \times 10^{-6}}{0.6 \times D^3}\right]^{5/2} \quad \text{if } D < 10^{-1}\ \text{mm} \quad \text{Eq. (3)}$$

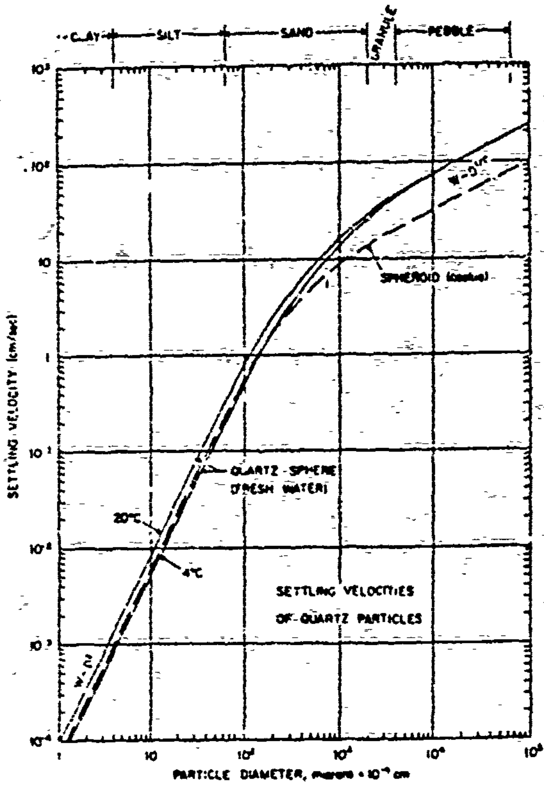


Figure 3-1 **Settling velocity for quartz spheres in dry air (at one atmosphere) and in fresh water for temperatures of 4°C and 20°C. The spheroid is assumed to fall in water in the direction of the minor axis, and the diameter is taken as that of a sphere of the same volume.**

The rated cone index (RCI) is calculated by multiplying the cone index values from equations (2) and (3) by the remolding index in Table 2-2 based upon the qualitative soils classification. Comparing these RCI values to Table 2-1 will give the wet trafficability estimates. Calculate the dry trafficability estimates by multiplying the wet RCIs by the dry percent strength ratios from Table 2-3 according to soils classification. Compare the dry RCIs with Table 2-1 to determine dry trafficability.

Advantages of this method are:

- Wet and dry trafficability can be assessed quantitatively from as little as a single sample taken under the break point for a two-dimensional beach.

- Other advantages equivalent to the previous discussion in section 3.2.

Limitations of this method are:

- Settling column required on the insertion platform.

- Swimmer/diver pairs must return bottom samples to the support ship for subsequent analysis.

- Equations (2) and (3) are based upon spherical shaped non-cohesive grains. This calculation is inadequate for silty clays and tends to underestimate trafficability in these cases.

- Complex three-dimensional shorelines may require many samples.

It should be remembered when applying this method that equations (2) and (3) are based upon some idealized assumptions. These equations are based upon a condition of static equilibrium between applied wave stress and dispersive pressures resulting from the immersed weight of the soils mass. The grains comprising this soil are assumed to be cohesionless spheres. The best results will be obtained for beaches comprised of class I soils from Table 2-2. Equations (2) or (3) will tend to underestimate cone indices and trafficability if beach sands contain significant amounts of shell fragments and other flat granular constituents. Furthermore, the best results are achieved for equilibirum beaches, where the wave climate has remained steady for significant periods of time, on the order of several days (Reference (11)).

3.4 Trafficability from SUROBS.

Under the assumption of an equilibrium beach profile, the smallest grain size appearing under the breakpoint will be that which is just moved from rest by the highest breaking wave. The drag velocity corresponding to the highest breaking wave should be referred to as the threshold drag velocity. A unique relationship exists between the threshold drag velocity and the grain size distribution on the beach (Reference (13)). The grain size distribution will in turn determine wet trafficability according to equation (2).

During a hydrographic reconnaissance, the SUROBS should include the wave height (trough to crest), H_b, the wave period T, and the water depth h at the breakpoint of the highest waves. If the depth of water at the breakpoint cannot be accurately determined by averaging depth gauge readings, it may be estimated from the breaker height observation using:

$$h \approx \frac{5}{4} H_b \qquad \textbf{Eq. (4)}$$

The threshold drag velocity is then calculated from these breakpoint SUROBS according to linearized wave theory as follows:

$$= \left[\left(\frac{H_b}{2}\sqrt{g/h}\right)^2 + \left(\frac{2\pi H_b}{T}\right)^2\right]^{1/2} \times \frac{0.356\ T}{\sqrt{g\,h}} \qquad \textbf{Eq. (5)}$$

where g is the acceleration of gravity = 980 cm/sec^2, and where h and H_b must be converted from feet to centimeters. Once the threshold drag velocity is computed in cm/sec, the corresponding mean grain size D_t can be determined using the empirical curve in Figures 3-1 or 3-2. The wet rated cone index is computed multiplying equations (2) or (3) by the corresponding remolding index from Table 2-2. The resulting wet RCI is referred to Table 2-1 to determine wet trafficability. The dry RCI is calculated by multiplying the wet RCI by the corresponding dry percentage strength ratio from the specific soil class in Table 2-3. The dry RCI is referenced to Table 2-1 to determine dry trafficability.

Advantages of this method are:

- No special equipment required.
- No grab sample must be taken or returned to insertion platform.
- Wet and dry trafficability may be determined from a submerged observation at the break point.

Limitations of this method are:

- The method does not calculate strength at the depth of the critical layer and may therefore underestimate true trafficability.
- The method is inaccurate if wave climate changes rapidly (on the order of several hours).
- The method is inapplicable to beaches without waves.

3.5 Trafficability from Geotechnical Diver Measurements.

In the complete absence or highly variable surf zone activity, indirect methods such as discussed in sections 3.3, 3.4, and 3.5 will be unsatisfactory. In this case, the use of a geotechnical diver tool during the hydrographic reconnaissance may be operationally suitable. In particular, the Miniature Standard Penetrometer (MSPT), shown in Figure 3-3, will give the most accurate of all possible trafficability estimates. This diver tool was developed by the Naval Civil Engineering Laboratory (NCEL) for use by the SEABEE Underwater Construction Teams (UCTs). This device is a miniaturized version of the standard penetration test (SPT) used worldwide by soils engineers to determine cone indices. However, the SPT itself is unsuitable for use by divers because it requires a 140 pound weight falling 30 inches, thereby relating the number of blows of this weight to a given penetration depth increment and cone index value (see Figure 2-2).

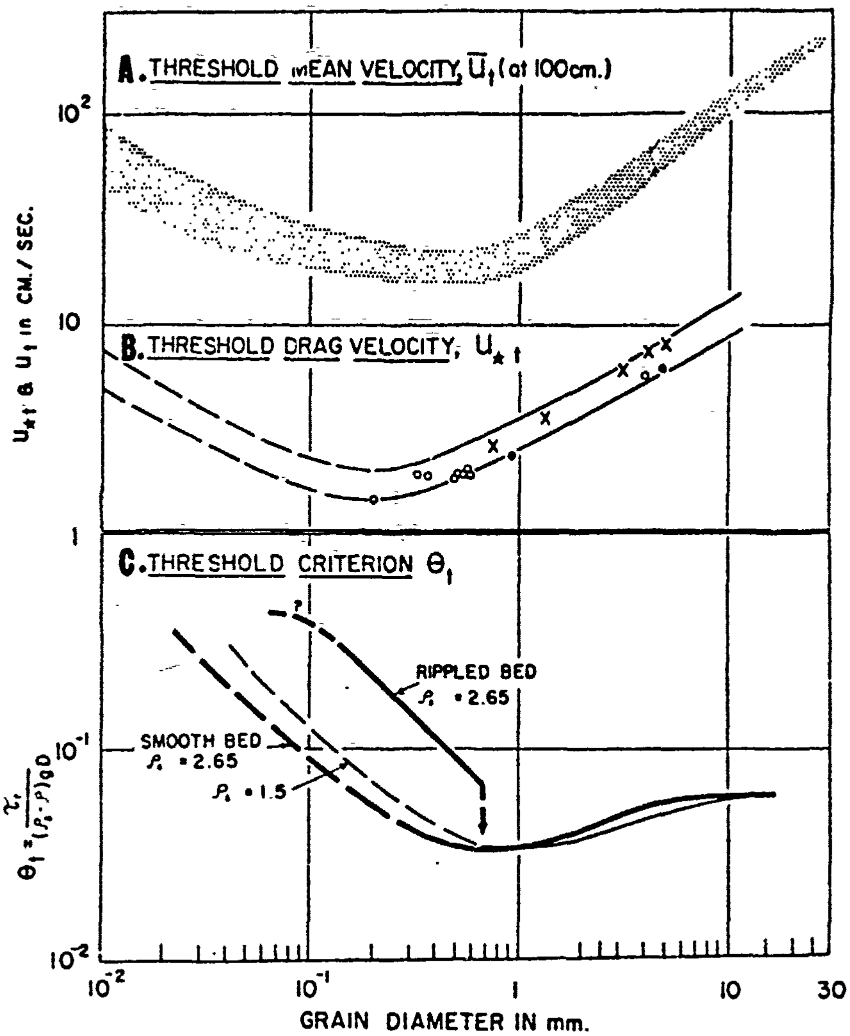


Figure 3-2 Dependence of grain size on a) threshold velocity, b) drag velocity, and c) shields parameter; from Reference (14)

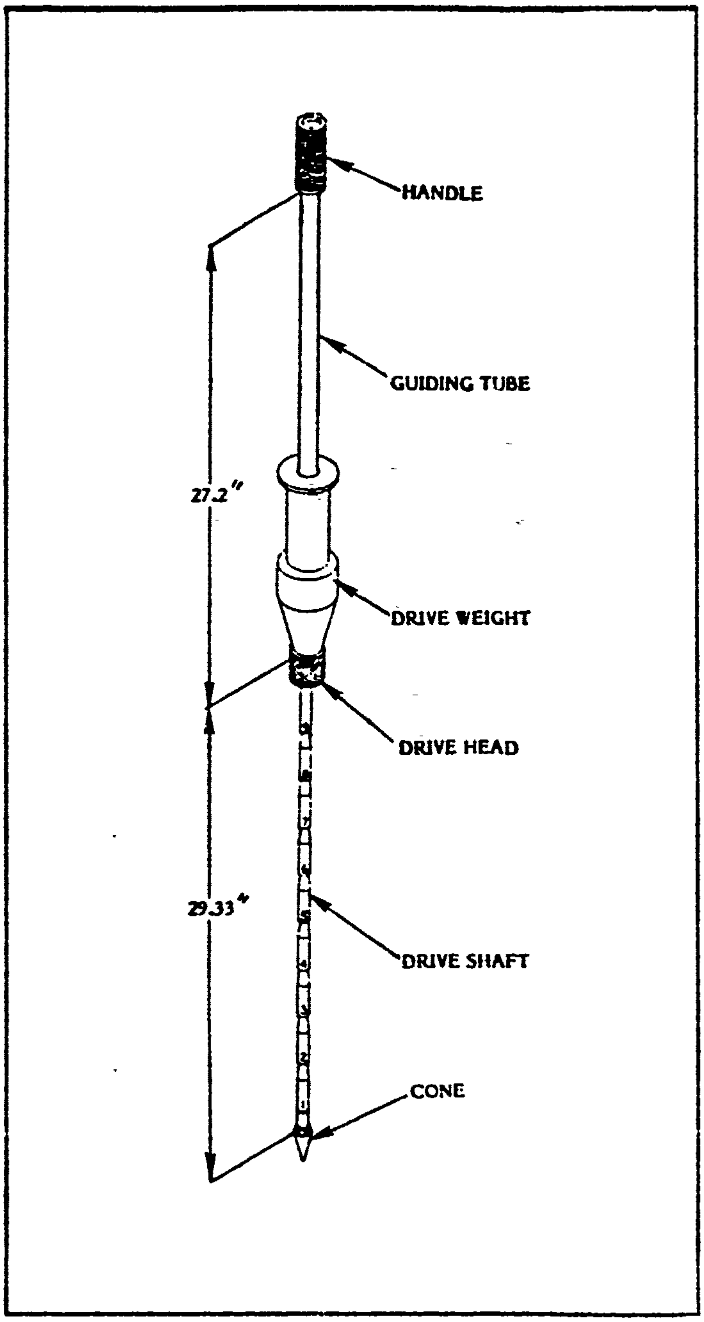


Figure 3-3 Miniature Standard Penetrometer (MSPT)

The MSPT uses the same basic idea as the SPT to deliver a blow, but with a necessary reduction in scale (see Figure 3-3). The device consists of four basic components: a cone, a drive shaft, a drive-head and guide tube, and a drive weight. The steel cone is 1.0 inch in diameter and has a 30-degree included angle. The cone attaches to a 36-inch long, 5/8-inch diameter aluminum shaft. The shaft, which is grooved in 3 inch increments, threads into an aluminum drive head. A steel slide hammer, having a dry weight of 11.6 pounds, is attached to the head via an aluminum guide tube. The drop distance of the hammer to impact is 18 inches.

The weight, which is raised by hand, is shaped to provide protection against pinching the user's hand. Initial trials with a lighter, less streamlined drive weight resulted in relatively high blow counts. The drive weight was modified by increasing its weight, tapering the lower end to reduce hydrodynamic drag, and grooving the end to reduce the cushioning effect of the trapped water upon impact.

Operating the MSPT involves two types of measurements, one static and the other dynamic. In the static test, the MSPT is placed on the soil surface and allowed to penetrate under its own weight. In sand, the depth of penetration will be less than 3 inches. In cohesive soils, the depth can be significantly greater, depending on the shear strength of the soil. Following the static penetration measurement, the MSPT is driven into the soil with the drive weight (Figure 3-3) to obtain a dynamic measurement. Blow counts are measured in 3-inch increments. The MSPT will not penetrate rock, and the results are adversely affected by the presence of shells or rocks.

For transport and storage the MSPT is disassembled by unscrewing the shaft from the anvil. The shaft is then inserted into the hollow handle with the cone protruding and screwed into a socket at the base. The drive weight is secured against the anvil with a clamp or length of line. In this manner, the MSPT telescopes down to only 29 inches in length for ease of penetration.

Considering the static measurement, a rudimentary analysis of the bearing capacity allows an estimate of soil penetration as a function of average soil shear strength. Assuming a constant shear strength with depth, a cone factor of 10 (ratio of cone penetration resistance to soil shear strength), a soil sensitivity of 3 (ratio of undisturbed shear strength to remolded shear strength), and full mobilization of remolded shear strength along the penetrometer shaft, then a rough correlation between static penetration depth and cone index values can be determined using the calibration curve in Figure 2-2.

For the dynamic measurements, correlating the blow count to sediment properties is more difficult. In the present case, the following approach to the problem was considered. The approach was to establish a tentative guide, shown in Table 3-1, for relating the MSPT blow count to soil conditions, based on analytic considerations similar to that done for Table 2-2 and using the same soil state assumptions. These theoretical correlations were made using the different physical parameters of the SPT and MSPT to establish a scaling of the SPT's blow count per 3 inches. While this does offer a starting point for interpreting the MSPT data, it does not quantitatively describe the sediment.

The qualitative soils class according to Table 3-1 is then related to a specific range of RCI according to Table 2-2; and then on that basis, determination of trafficability is made according to Table 2-1. When the MSPT is used beneath the break point or surf zone, the results can be converted to dry trafficability by multiplying the wet RCIs by the dry percentage strength ratios from Table 2-3. Compare dry RCIs to Table 2-1 to determine dry trafficability.

Field tests of the MSPT were conducted at: Sanjon Creek, Ventura, Port Hueneme Beach, San Nicolas Island, Hollywood Beach, and Ormond Beach, California (Reference (11)). These tests led to a number of modifications to the device, including increasing the drop height and mass of the drive weight in order to reduce the number of blows required to achieve penetration. The modifications were made to maintain the divers' enthusiasm and proper execution of the test. Both degrade as the number of blows at one site increases. The divers prefer the slightly increased handling and swimming problems associated with a heavier drive weight in order to decrease the number of blows and bottom time required for the measurement. For operations at some sites, the use of a small, inflatable lifting tube was judged very helpful to compensate for the in-water weight of the MSPT and to improve its swimmability. Even with these improvements, the device is fairly long in its present configuration, which caused some difficulty at sites with higher currents or bottom surge. A shorter rod having a 12 to 14 inch penetration capability would be more suitable to applications assessing beach trafficability, since penetration to the critical layer is the only requirement.

Table 3-1

Tentative Guide of Blow Count to Soil Condition

Blows (3-inch Increment)	Soil Conditions	Soil Class
1	Medium clay (1 psi)	IV
2	Firm clay (2 psi)	II
3	Very loose sand	III
10	Loose sand	I
30	Medium sand	I
60	Dense sand	I

The diver's evaluation of this device showed that it satisfied its exploratory development objectives. In order to enhance its effectiveness as a geotechnical tool further testing by the SEAL teams appears advisable at this time. In particular, testing by surface swimmers during a night reconnaissance is needed to determine suitability in this operational mode. All testing by NCEL to this point addresses only conditions for a submerged reconnaissance by divers using breathing apparatus. The MSPT appears from these tests to be well suited to making wet trafficability measurements on the beach within the surf zone. Whether the device is also well suited operationally to direct measurements of dry trafficability on the dry foreshore and backshore regime of the beach by a swimmer exiting the water in a night reconnaissance is another question which needs an operational evaluation. The primary concern here would be the noise level while performing blow counts in the dynamic mode. If this level were unacceptably high in spite of background surf noise, then it could still be used in the static mode, which does not require a blow count as discussed previously. From the soil engineering standpoint, the MSPT should be capable of determining dry trafficability with greater precision by direct measurements on the dry beach surface than indirect methods previously discussed.

Advantages of this method are:

- Direct measurement of soils strength and thereby greater quantitative accuracy.
- Can measure trafficability by either a noise free static mode, or by blow counts in the dynamic mode.
- Can be used on non-equilibrium beaches or beaches without waves.

Limitations of this method are:

- Weight and bulk of the MSPT diminishing swimmer or diver endurance.
- Potential detectablility of blow counts due to noise when used in the dynamic mode.

Chapter 4
Determination of Trafficability by Remote Sensors

4.1 General.

Techniques for remote sensing have been developed that can be used for initial determination of beach trafficability over a large number of beaches. Although not as accurate as direct observation by swimmers, remote sensors provide a "beach feasibility study," eliminating the need to place swimmers on marginal beaches and optimizing the limited swimmer assets over fewer candidate beaches.

4.2 Aerial Penetrometers.

This method proceeds identically to that outlined in section 3.5 and gives the same information derived from the geotechnical measurements by divers. The difference is that the penetrometer is delivered by aircraft rather than by a swimmer or diver team.

The high penetrating power attained by even a small light object when dropped from an aircraft can be utilized for a test of surface bearing strength. If the object is equipped with an indicator of the depth of or resistance to penetration, then the soil can be classified as to trafficability. Measurements of depth of penetration by such an object in various soil types have given valid correlation with standard cone index values.

An instrument operating on this principle, called an aerial penetrometer, has been developed to enable the determination of bearing strength from an aircraft without the necessity of landing (Reference (9)). It is essentially an extension of the manual cone penetrometer (SPT) to remote indication of measurement.

Figure 4-1 shows a plot of an aerial penetrometer depth penetration versus cone index value for a variety of soils on which this instrument was tested during its development and in an operational suitability trial.

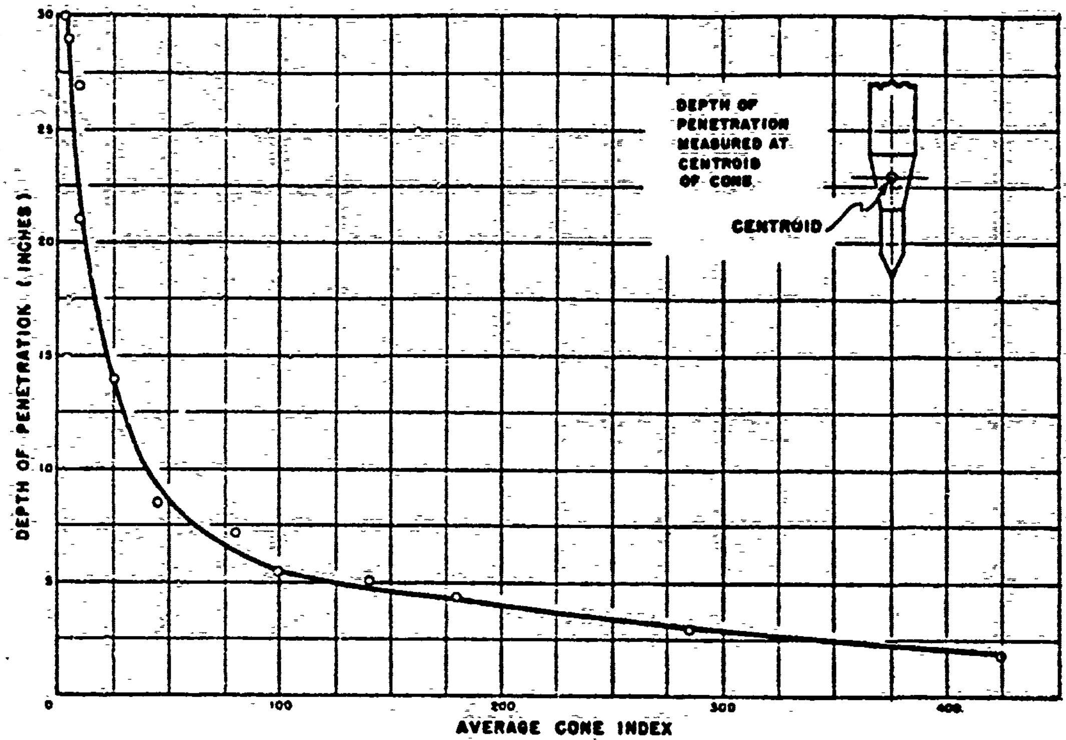


Figure 4-1 **Plot of aerial penetrometer depth penetration versus cone index value for a variety of soils on which this instrument was tested during its development and in an operational suitability trial**

The aerial penetrometer consists of an aluminum cylinder approximately 2 feet long, 1.5 inches in diameter, and weighing approximately two pounds. It is equipped with pop-out vanes for stability and governing of terminal velocity during fall, and has a cone-shaped point to penetrate the ground. Figures 4-2 and 4-3 show views of the instrument. It is designed to be dropped by hand from reconnaissance or liaison type aircraft or potentially by an RPV over unexplored beaches and terrain, and indicates by means of a single flare signal the supporting capacity of the soil. Upon striking the surface, the depth or impact of penetration ejects the indicator by a shotgun type cartridge when the aerial penetrometer falls on soil as strong or stronger than the rating of the penetrometer. These ratings have been calibrated to cone index vehicle mobility standards.

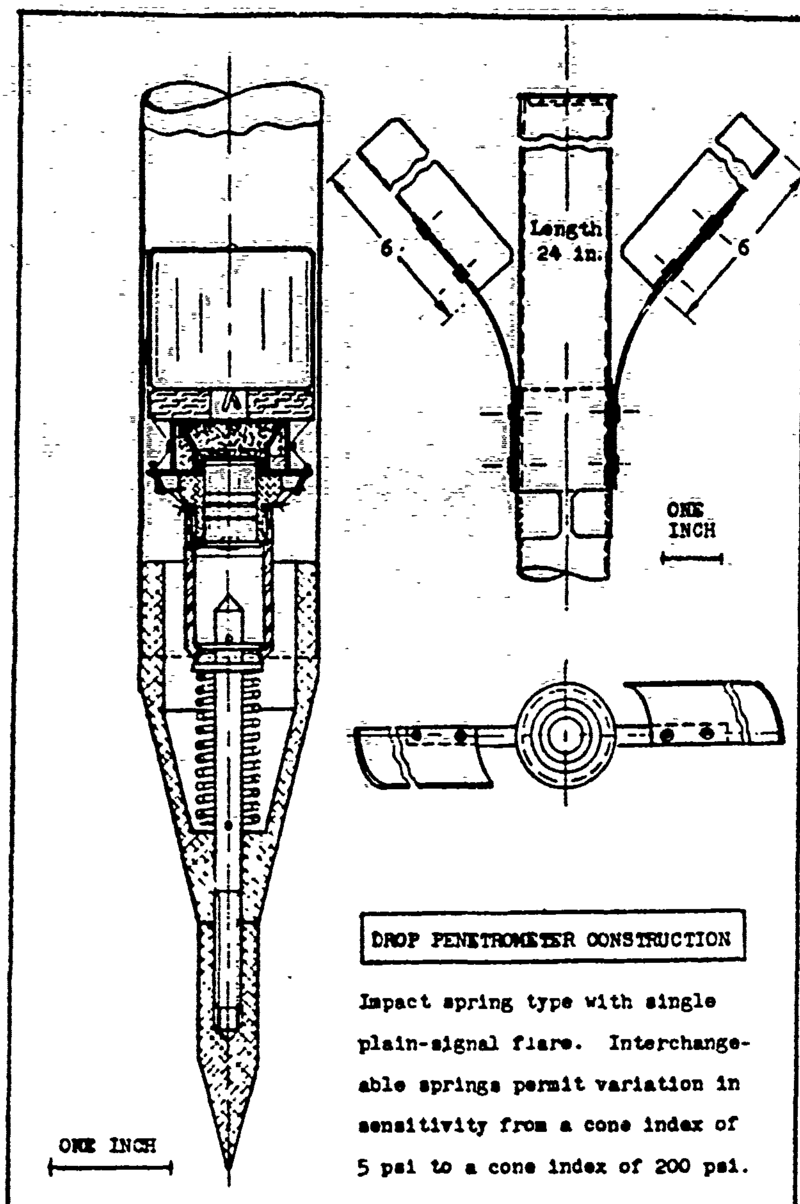


Figure 4-2 Drop penetrometer for cone index range 5 - 200 psi

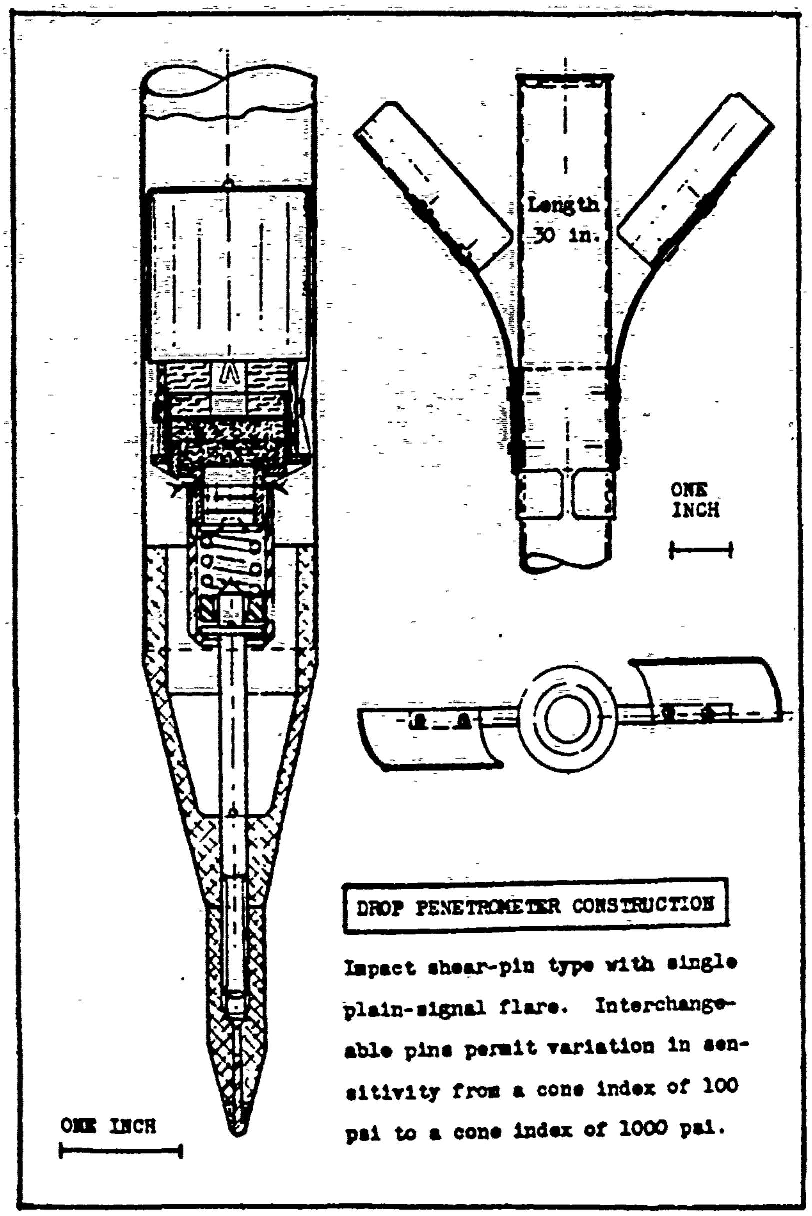


Figure 4-3 Drop penetrometer for cone index range 100 - 1000 psi

In penetrometers of low ratings (cone index 5 - 200) a spring is used to fix the impact force required to activate the signal, while different sized shear pins are used in penetrometers with higher ratings (cone index 100 - 1000). Figures 4-4 and 4-5 show a constructed assembly for these two types of instruments, and Figure 4-6 is an engineering drawing of the penetrometer parts. The cartridge primer is detonated upon impact if the impact is of sufficient magnitude to all the flare and cartridge to overcome the resistance of the spring or shear pin and strike the firing pin. The terminal velocity of the aerial penetrometer becomes constant at approximately 100 ft/sec after falls of 400 feet or over. The only parameter determining the release of the flare indicator is the strength of the ground. The signal is not activated when the penetrometer falls on ground softer than its rating.

The main usefulness of a "go-no-go" type aerial penetrometer with a single indicator is for reconnaissance of an unknown area for landing of one particular type of vehicle. The pilot need not be concerned with a whole range of trafficability properties of the intended landing area but needs to know only whether or not the "cone index" of the beach is at least that required for particular vehicles. The release mechanism of the indicator is set for that determined value and a sufficient number of penetrometers are dropped.

If they consistently give a positive signal, then a landing can be safely attempted. If no signals issue or if they are erratic, the indication would be of intermittent soft and hard spots, and the area would be unsuitable.

Other models experimentally developed employ multiple signals from three flares, which place the soil bearing strength between pre-set numerical cone index values. These are useful if the particular vehicle mobility standards are not known and general trafficability information is desired or if contour lines of trafficable areas are to be drawn. Figure 4-4 is a diagram of this type of construction. The number and limits of trafficability classes distinguishable by this type of aerial penetrometer can be varied to suit any particular purpose.

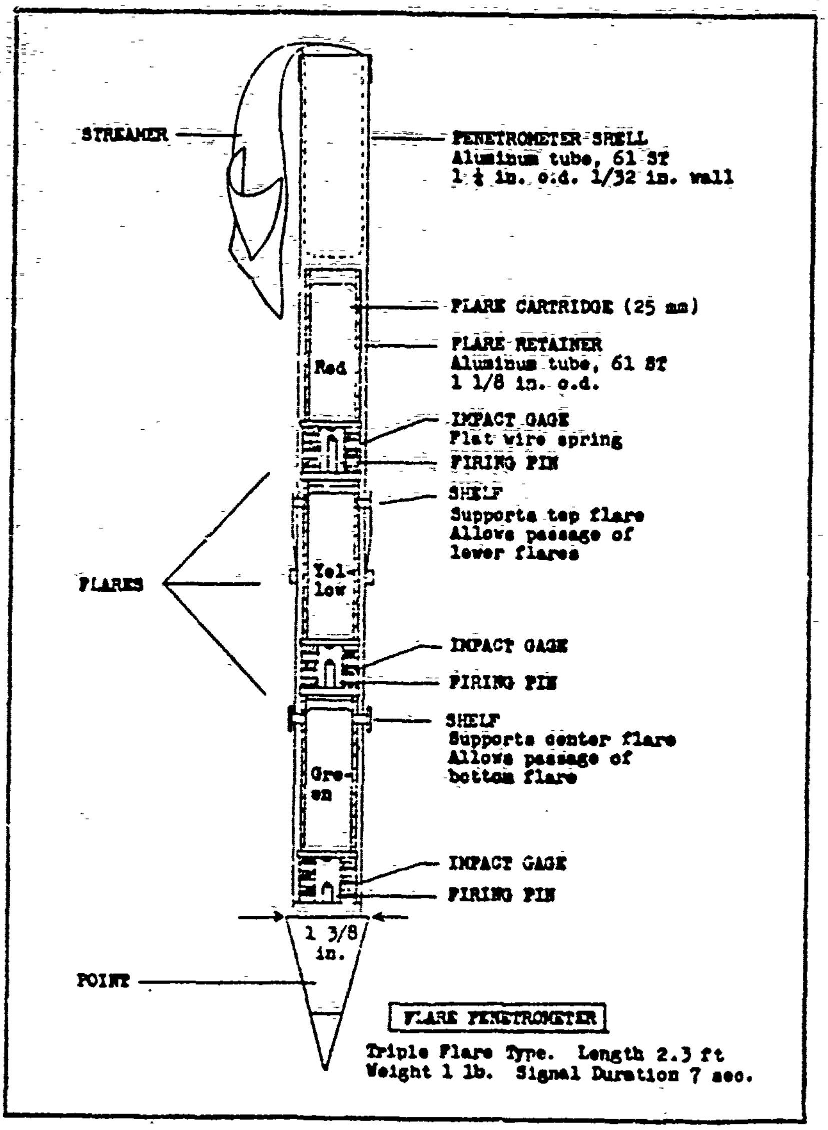


Figure 4-4 Detail of flare penetrometer

Figure 4-5 Photograph of the assembly of a telemetering penetrometer

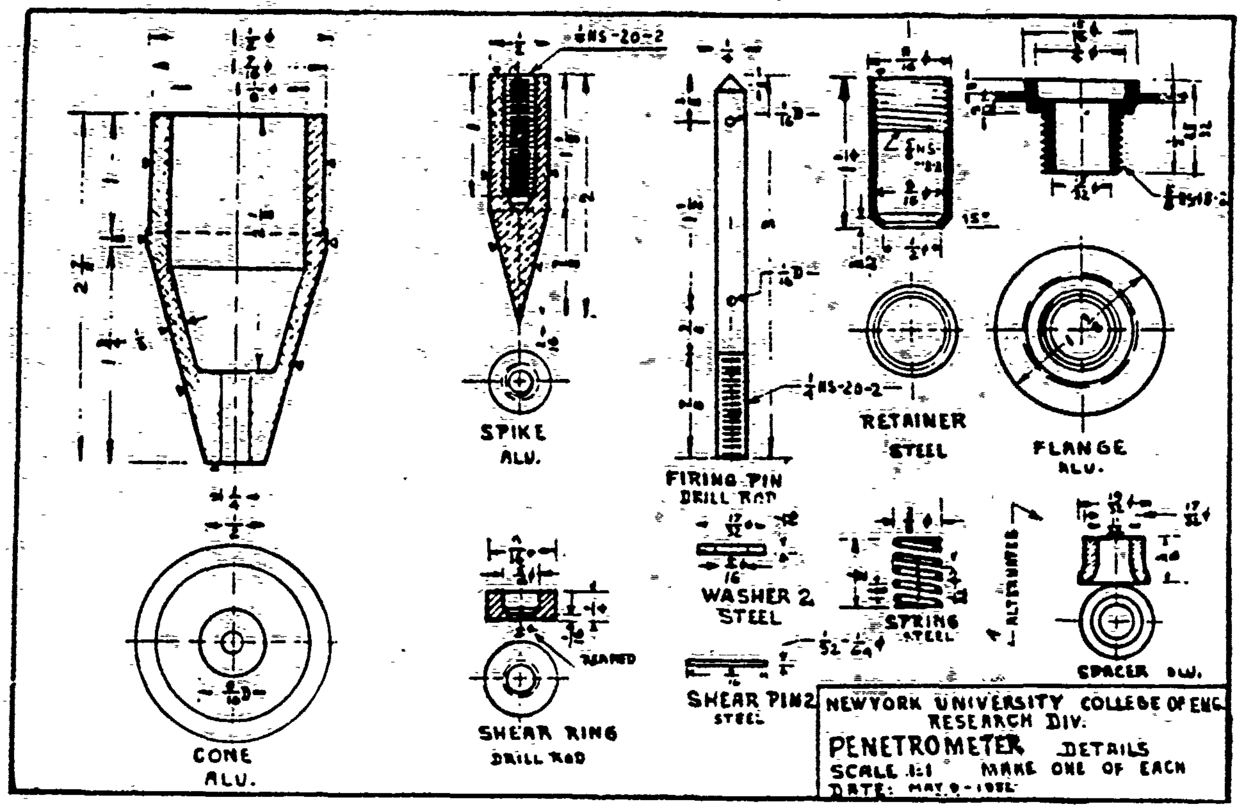


Figure 4-6 Engineering drawing of the aerial penetrometer components

Another type of aerial penetrometer experimentally developed employs a radio telemetered indicator by which signals in the frequency range of 4 to 8 megacycles can be picked up by a receiver in the aircraft in the form of sound whose pitch varies in fixed intervals proportional to the firmness of the soil. The transmitter in the penetrometer is capable of 1/2 hour continuous operation, emitting signals receivable at approximately four miles distance. Figure 4-5 shows a photograph of the assembly of a telemetering penetrometer.

The manual cone penetrometer (SPT) determines the static penetration resistance with minimum displacement of soil. However, the aerial penetrometer strikes the ground with a definite kinetic energy which is two to four times as great as the work performed by the static penetrometer, and results in displacement of the soil through deformation and partial destruction of the natural (thixotropic or structural) ground strength. This, in turn, causes partial remolding of cohesive soils and liquefaction of water-bearing sands. In weak soils, a relatively large volume is displaced and deep penetration occurs. Tough soils absorb the kinetic energy within a short distance, with shallow penetration resulting. Similar action takes place under light traffic, hence the indication of the aerial penetrometer is directly related to the soil capacity to support limited traffic.

For all-aircraft use of the aerial penetrometer, the technique should be to fly into the wind and drop the penetrometer directly over the target, with due allowance for wind effect on penetrometer during fall. This procedure was adopted as standard for the operational suitability test and yielded excellent results with all types of aircraft used. The first drops were always well within the area of the hypothetical landing zone to be explored.

Where only a few of the go-no-go type are to be used, the unit can be dropped either by the pilot or by a crew member from a window or door of the reconnaissance aircraft. Where many units must be dropped for a thorough investigation of a large area, launching racks and release mechanisms, similar to bomb or rocket racks under the aircraft, should be considered.

The aerial penetrometers are very simple in construction, have few moving parts, and are exceptionally sturdy. Figure 4-6 shows an exploded view of the internal parts of an aerial penetrometer. The 6 inch stabilizing fins assure aerodynamic stability during fall and a vertical orientation upon impact. An operational suitability test discussed below included safety tests of penetrometers equipped with flare indicators. One such unit, with the spring mechanism set for the weakest soil trafficable by aircraft, was dropped point-down three times on an asphalt concrete pavement from heights of 4 to 6 feet without detonation. For safety, the spring type spacer would seem preferable to the shear pin type. While packed inside a cardboard launching tube, the penetrometer is immune to vibration, shaking or dropping occurring in handling or transportation. Propeller or centrifugal type safety catches are under consideration as additional safety measures.

The advantage of this method is:

- A large number of candidate beaches can be investigated without incurring risks due to swimmer/diver deployment.

The limitations of this method are:

The obvious limitation in the use of the aerial penetrometer as a trafficability indicator is the necessity of dropping a large number of them to thoroughly explore an area where a landing is contemplated. This results from their inability to function in the surf zone where wave shear sorting has already graded the soil. An evaluation by Stevens Institute of Technology for the Army Ordnance Corps cites this fact, recommending a mimimum coverage of 2,500 square yards (or an area 50 yards per side) for each penetrometer in an inhomogenous soil. This estimate appears to require an excessive number (20) for a 1,000 yard invasion lane on an otherwise unbounded two-dimensional beach. There is simply not that much longshore variation to justify so high a sampling density. Perhaps a fully three-dimensional pocket beach may require 20 per 1,000 yards, but 4 to 8 would seem adequate for 1,000 yards of two-dimensional beach.

There is the possibility of erroneous indication from penetrometers which strike a stone, a clump of moss, a rabbit hole, etc., which might occur in unexplored inhomogenous soil. However, such false indications would be infrequent and statistically insignificant in any reasonable number of penetrometers dropped to cover an area necessarily large enough for landing operations.

There may be difficulty accurately linking a given trafficability indicator signal with its appropriate individual penetrometer. It is also difficult to precisely determine the penetrometer's location. These difficulties may be solved through technological advancements. An optical-photographic method, where the penetrometer indicator would be a coded light emitted by each instrument upon impact, shows promise. A photographic reconnaissance aircraft lagging behind the delivery aircraft would photograph the area being investigated and obtain an accurate record of the entire coverage. At present, the flare type peneotrometer does not appear to be fully clandestine. The most desirable version for clandestine activities would be the radio-telemetry based aerial penetrometer. Wet trafficability is not directly measured but can be calculated using Table 2-3 from trafficability estimates obtained on the dry foreshore or backshore.

4.3 Aerial Photographs.

This method was employed during WWII with considerable success. There have been little or no advanced studies of this method since that time (Reference (14)). The trafficability estimates obtained are qualitative in nature due to scatter in observational results.

The basic elements of this approach involve determining either the average drying farshore slope or width as derived from an aerial photograph, and then using empirical curves (see Figures 4-7 and 4-8) to determine corresponding median grain sizes. Once the median grain size has been determined, the cone indices are calculated from equations (2) and (3) and trafficability assessed according to Table 2-1 after correcting for remolding in Table 2-2.

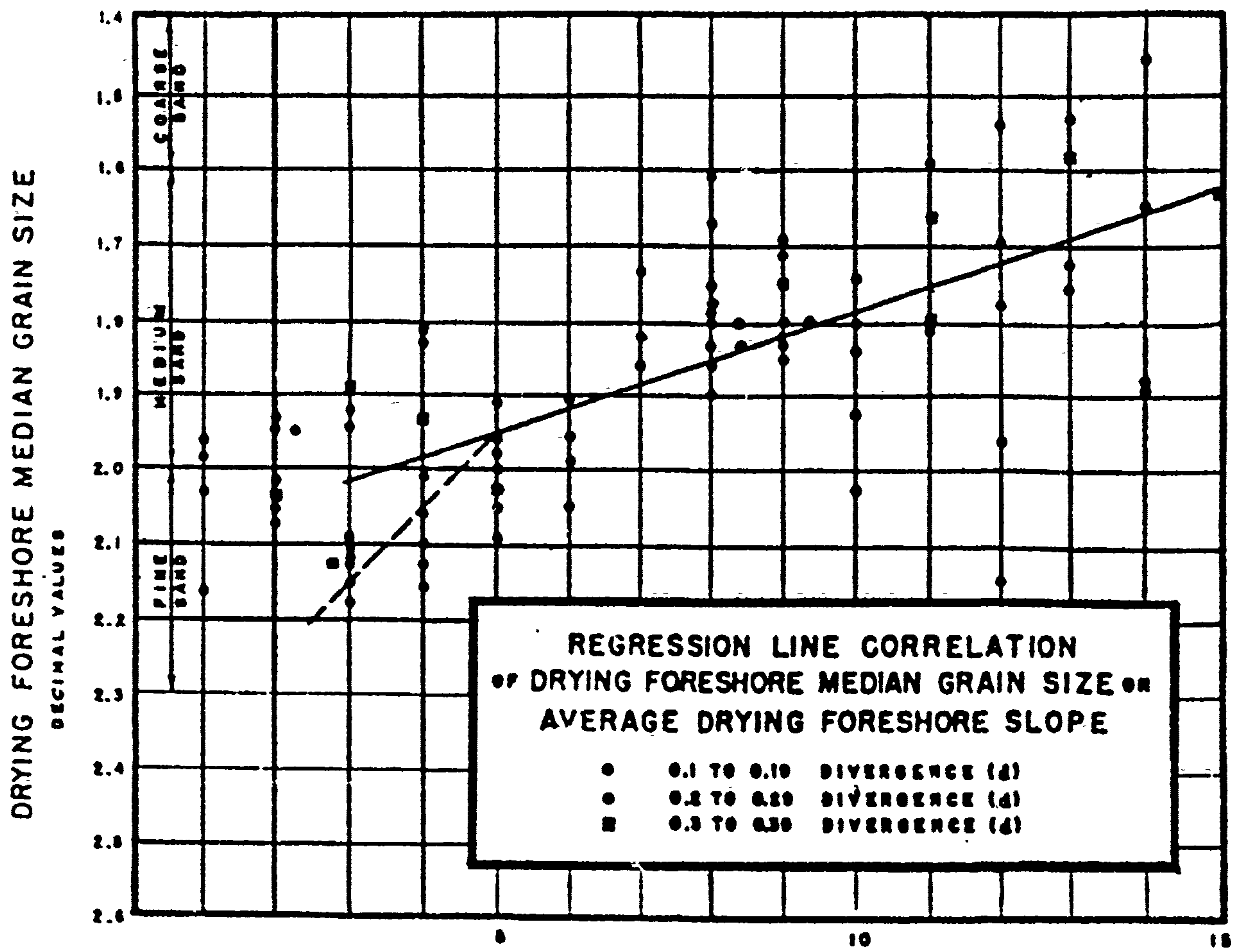


Figure 4-7 Grain size dependence on average drying foreshore slope (%)

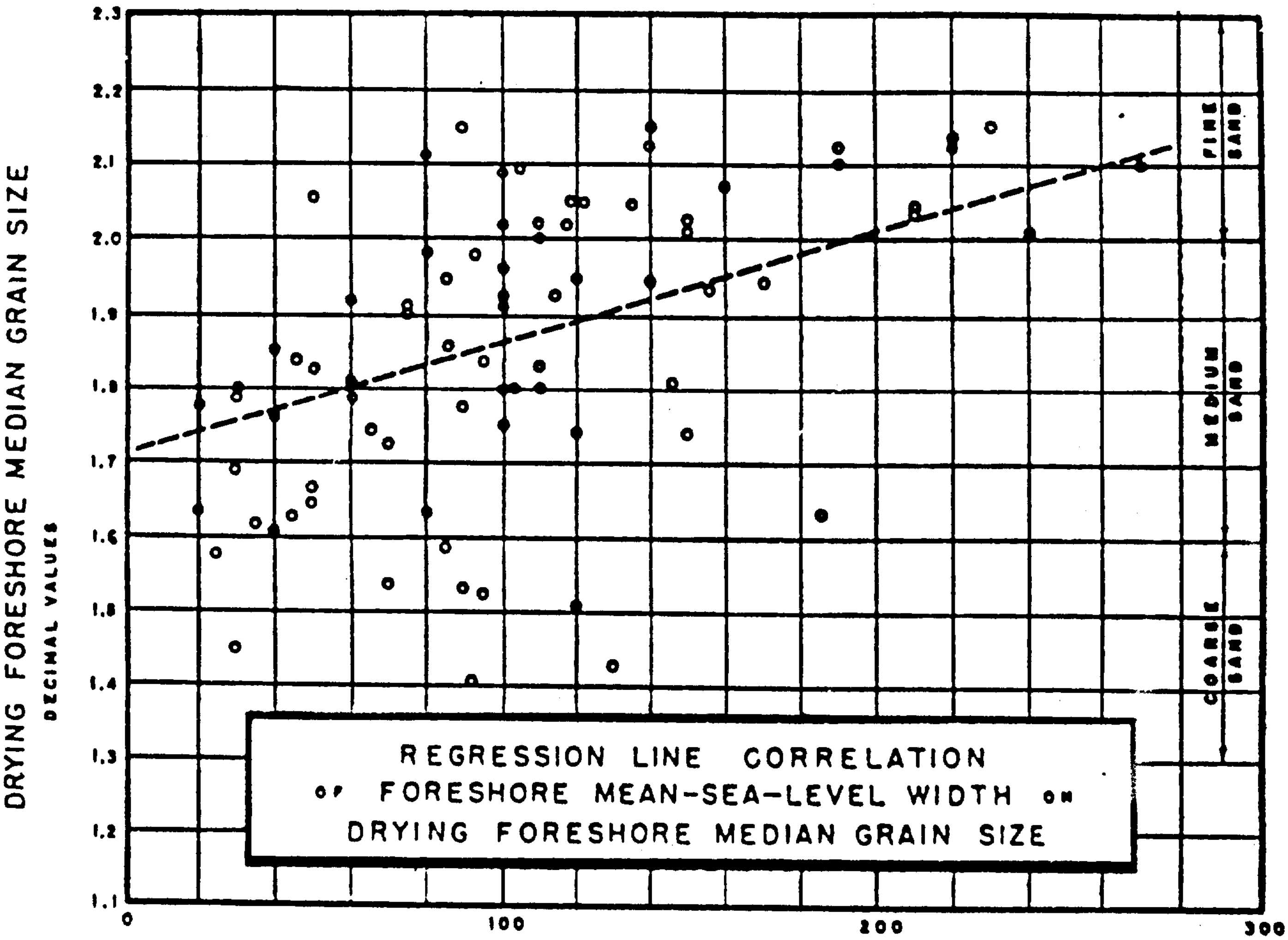


Figure 4-8 Grain size dependence on foreshore mean-sea-level width (ft)

Table 4-1 presents recommended specifications for aerial photography that is to be used in making estimates of beach trafficability:

Table 4-1

Aerial Photography Specifications for Estimating Beach Trafficability

Item	Specification
Scale	1:2500 or larger
Direction of Flight	Parallel to waterline
Type of Photography	Conventional vertical with standard stereoscopic overlap, or Some vertical with stereoscopic coverage (only if it is believed that slopes can be estimated with sufficient accuracy)
Coverage	Two thirds land and one third water with principal point of photograph on the beach face
Time of Photography	During a period two hours before to two hours after low tide
Film-type and Finish	Black and white, Super XX, Tri-X (or equivalent) glossy finish
Filters	Standard

The first step in an estimation of beach trafficability is a division of the beach into zones.

The beach is an area extending landward from the mean low water line to a marked change in material or landform, or to a permanent vegetation line. It may be divided into four sub-areas, which may be designated as:

1. The wetted foreshore
2. The drying foreshore
3. The backshore
4. The forward dune apron

The wetted foreshore is arbitrarily defined as that part of the beach which is alternately but frequently covered and uncovered by shallow water swash at any given tide stage. The wetted foreshore is saturated or almost completely saturated at all times. Its boundaries are indefinite. Naturally, since it is a function of tide stage, it moves up and down the beach face.

The drying foreshore is that part of the beach lying between the landward boundary of the wetted foreshore and the average point of maximum uprush at high tide. At any given tide stage, the drying foreshore is completely exposed to the air and has moisture contents ranging from nearly saturated at the wetted foreshore boundary to nearly dry at its inland boundary. The width of the drying foreshore varies from a maximum at low tide to zero at high tide. THE DRYING FORESHORE ZONE IS THE MOST VALUABLE INDICATOR OF BEACH CONDITIONS.

The backshore extends inland from the average point of maximum uprush at high tide to a marked change in material or landform, or to the line of permanent vegetation. The backshore, by definition, is beyond the zone of wave action. Consequently, it is composed of loose sand with very low surface moisture content. It is of little value in predicting beach conditions.

The forward dune apron is an area of transition between the backshore and the dune zone if dunes are present. It is composed of soft, dry sand in practically every case. It is of little value in predicting beach conditions.

The delineation of the various zones is not always easy on an aerial photograph. However, in general, they will appear as follows:

1. <u>Wetted Foreshore</u>. An even-toned dark area close to the surf zone. May often be partially or completely obscured by uprushing swash water. At low tide the zone is narrow in comparison to the remainder of the foreshore.

2. <u>Backshore</u>. A light toned area, flat or sloping, extending from a point near the dunes, seaward to a definite zone or line where the tone

becomes visibly darker. This area may be coincident with a line of cusps, a scarp or a slope change (berm). It is not always coincident, however. The zone of darkening is often coincident with a zone of debris and seaward accumulation.

3. Drying Foreshore. That area of the beach between wetted foreshore and backshore. It has tones which are intermediate between those of the backshore and those of the wetted foreshore. The tones may be uniform or may vary due to slope changes, low spots, debris accumulations or increasing surface moisture contents.

The determination of the average foreshore slope (AFS) is one of the most important steps in completing an estimate of beach conditions. Unfortunately, it is also one of the hardest. The difficulty is not related to the concept itself, but rather to its physical determination from aerial photographs.

If a rough estimate of slope is allowable, it is acceptable to place the average foreshore slope into one of five categories:

1. less than 3%
2. less than 5%
3. between 5% and 10%
4. between 10% and 15%
5. greater than 15%

If the average foreshore slope cannot be definitely placed in one of these categories, it is best to neglect the slope indication in formulating an estimate of beach conditions.

The determination of slope is further complicated, in many instances, because it is an average slope. The foreshores of many beaches often display more than one slope. The average foreshore slope represents their rough graphical average. The graphical average is best obtained by plotting the slopes and drawing an average line through them by eye.

Rough foreshore slopes can often be estimated in terms of other visible features, such as breaker patterns, tone patterns, width, etc. Based upon the average foreshore slope estimate, the median grain size can be determined using Figure 4-7. From this point, the median grain size determination will yield wet and dry trafficability estimates following procedures outlined under section 3.3.

The foreshore mean-sea-level width (Fs MSLW) is determined as follows:

1. Measurement of the horizontal extent of the exposed foreshore (including the visible portion of the wetted foreshore) and its conversion to feet.

2. Determination of time of photography from the marginal data on the aerial photograph.

3. Determination, from available tidal data, of the vertical distance in feet between the tide stage at the time of photography and mean-sea-level. If the tide stage is below mean-sea-level, the vertical distance is negative. If the tide stage is above mean-sea-level, the vertical distance is positive.

4. Calculate the average foreshore slope S, from the horizontal distance x in Step 1 and the vertical distance V in Steps 2 and 3, using the following equation:

$$S = \frac{100V}{x}, \qquad \text{Eq. (6)}$$

where:

x = a horizontal distance (feet)

V = the vertical difference between tide stage at time of photography and mean-sea-level (feet)

S = average foreshore slope (%)

5. Application of distance x, according to sign, to the horizontal extent of the exposed foreshore determined in accordance with Step 1.

The result of these computations may be accepted as a sufficiently accurate measure of the foreshore mean-sea-level width.

An example of the computations follows:

1. Width of exposed foreshore = 200 feet

2. Tide stage at time of photography = 2 feet above mean low water

3. Mean-sea-level = 3.5 feet above mean low water

4. Difference between tide stage and mean-sea-level = 1.5 feet

5. Average foreshore slope = 3%

6. $x = \frac{(100)(-1.5)}{3} = -50$ feet

7. MSLW = 200 - 50 = 150 feet

The mean sea level width of the foreshore will then yield an estimate of the median grain size using Figure 4-8. At this point subsequent evaluation of wet and dry trafficability follows from the median grain size according to the methods outlined in Chapter 2, "Clandestine Methods."

Advantage of this method is:

- Remote imagery from satellites and aircraft can be employed to assess trafficability in hostile territory. This bases special advantages in rapid beach feasibility assessments.

Limitations of this method are:

- CANNOT BE USED IN TIDELESS SEAS.

- The accuracy is less than determination by direct observation, as described in Chapter 2.

4.4 Multispectral Scanner (MSS).

Remote sensing spectral data from satellite or aircraft have proven capable within the last ten years of delineating outcrop lithologies for mineral exploration. It has been recently demonstrated that these methods can be used to determine minerology, grain size, and moisture content of beach sands (Reference 17). Hence these grain size and moisture data from a multispectral scanner (MSS) can be applied to equation (2) or (3) to yield trafficability estimates following the method outlined in section 3.3.

Before grain size or moisture can be determined from MSS reflectance, it is necessary to determine the predominant mineralogy of the beach sand. There are five basic mineral groupings for which linear regression equations of hemipherical reflectance spectral have been developed. These groups are: 1) Iron-stained quartz Atlantic coast, 2) Iron-stained quartz Michigan coast, 3) Non-iron stained quartz, 4) Carbonate, and 5) Heavy mineral. The native sands of a potential target beach may be determined to belong to one of these five mineral groupings according to geologic maps or Mine Pilot Reports of the target area, or according to the characteristic spectra of these minerals as described in Reference 17.

Once the characteristic mineral group has been determined, the grain size and moisture can be determined based on hemispherical reflectance in 17 discrete spectral bands of the MSS. These bands are described in Table 4-2 below:

Table 4-2
Wavelength Ranges of Spectral Bands

Band Number	Wavelength Range (Meters^{-6})	Band Number	Wavelength Range (Meters^{-6})
1	0.43 - 0.47	10	0.75 - 0.80
2	0.47 - 0.49	11	0.80 - 0.90
3	0.49 - 0.51	12	0.90 - 1.00
4	0.51 - 0.53	13	1.00 - 1.10
5	0.53 - 0.56	14	1.10 - 1.20
6	0.56 - 0.59	15	1.20 - 1.35
7	0.59 - 0.63	16	1.50 - 1.85
8	0.63 - 0.67	17	2.10 - 2.50
9	0.70 - 0.75		

The MSS spectra taken over the target beach are examined in each of these seventeen bands to determine the reflectance energy for each band, (this energy is expressed by the notation " $\langle \text{Band } \# \rangle$ "). Grain size and moisture content are calculated by substituting the reflectance energy from the appropriate spectral bands into the linear regression equation associated with that particular mineral grouping:

(A) <u>Iron-stained quartz Atlantic coast:</u>

$$\text{Grain Size (mm)} = 6.87 - 3.4634 \langle \text{Band } 7 \rangle^{1/4} + 0.030 \langle \text{Band } 1 \rangle + 0.01672 \langle \text{Band } 15 \rangle \quad \text{(Eq.}$$

$$\text{Moisture \%} = 67.964 - 65.046 \frac{\langle \text{Band } 16 \rangle}{\langle \text{Band } 14 \rangle} \quad \text{(Eq.}$$

(B) <u>Iron-stained quartz Michigan coast:</u>

$$\text{Grain Size (mm)} = 0.6405 - 0.0152 \langle \text{Band } 5 \rangle - 0.0047 \langle \text{Band } 17 \rangle \qquad \textbf{(Eq. 8)}$$

$$\text{Moisture \%} = 60.149 - 49.961 \frac{\langle \text{Band } 16 \rangle}{\langle \text{Band } 11 \rangle} - 2.226 \frac{\langle \text{Band } 17 \rangle}{\langle \text{Band } 1 \rangle} \qquad \textbf{(Eq. 9)}$$

(C) <u>Non-iron stained quartz:</u>

$$\text{Grain Size (mm)} = 1.158 - 2.3284 \langle \text{Band } 10 \rangle + 0.3201 \frac{\langle \text{Band } 7 \rangle}{\langle \text{Band } 1 \rangle} + 0.2858 \langle \text{Band } 16 \rangle \qquad \textbf{(Eq. 10)}$$

$$\text{Moisture \%} = 127.02 - 65.159 \frac{\langle \text{Band } 16 \rangle}{\langle \text{Band } 15 \rangle} - 64.065 \frac{\langle \text{Band } 15 \rangle}{\langle \text{Band } 14 \rangle} \qquad \textbf{(Eq. 11)}$$

(D) <u>Carbonate:</u>

$$\text{Grain Size (mm)} = 5.9628 - 6.42 \frac{\langle \text{Band } 14 \rangle}{\langle \text{Band } 17 \rangle} + 1.081 \langle \text{Band } 14 \rangle + 0.1538 \langle \text{Band } 17 \rangle \qquad \textbf{(Eq. 12)}$$

(E) <u>Heavy Mineral:</u>

$$\text{Grain Size (mm)} = .19284 + .11194 \frac{\langle \text{Band } 14 \rangle}{\langle \text{Band } 17 \rangle} - 1.081 \langle \text{Band } 14 \rangle + 0.1538 \langle \text{Band } 17 \rangle \qquad \textbf{(Eq. 13)}$$

Laboratory ground truth measurements of these equations show an 88% correlation with grain size, and a 96% correlation with moisture content (Reference 17).

Having determined the grain size in millimeters for the appropriate mineral group from Equations 6, 8, 10, 12, or 13, convert to inches and calculate the cone index from either Equation 2 or 3. Based on the grain size classification in Figure 3-1 (sand, silt, clay, and so forth), refer to Table 2-2 for the appropriate remolding index. Multiply the result of Equation 2 or 3 by the remolding index to calculate the RCI. Determine the moisture content from Equation 7, 9, or 11 and refer this value to Table 2-3 for the appropriate percentage of saturated wet strength. Multiply the RCI by this value and refer to Table 2-1 for the trafficability.

Advantage of this method is:

- Satellite MSS reflectance data can be employed to survey large regions in a beach feasibility study.

Disadvantages of this method are:

- MSS regression equations require prior knowledge of beach mineralogy.
- MSS ground truth on beach mineralogy classification is not well developed at the time of this writing.
- Ground truthing of the linear regression equations has been accomplished primarily by laboratory measurements. A limited body of MSS reflectance data taken from aircraft have substantiated these equations for Lake Michigan beaches.

APPENDIX A

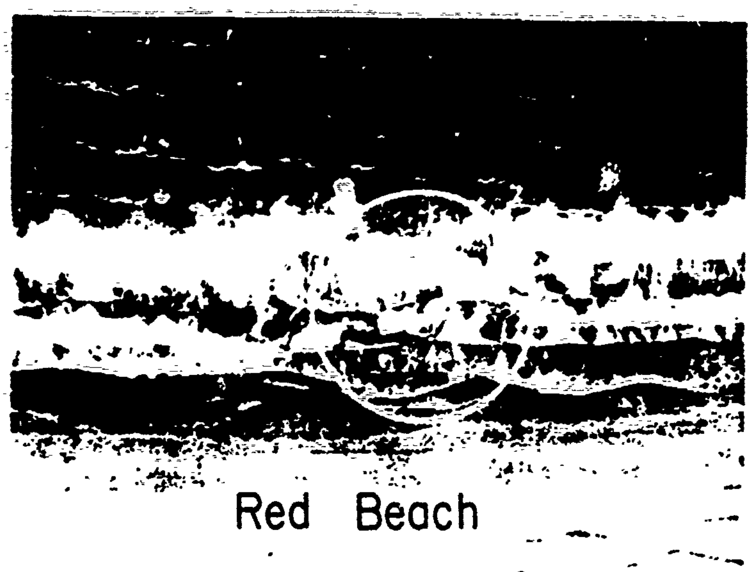
Examples of Beach Trafficability Calculation Employing Various Calculation Methods

A.1 Background.

Satellite photos show a barrier beach 10,000 yards in length (Figure A-1). The barrier beach forms a sand spit at one end and terminates at the foot of a rocky headlands at the other. "Red Beach" is a 1,000 yard wide potential invasion lane equidistant between the two ends of the barrier beach. The range of diurnal tides is -0.1 to +0.4 MSL. It is late summer and the weather over the offshore waters has been dominated for several months by a stationary high pressure system producing 20 to 30 knot winds. An archepelego located 300 nm offshore shelters the beach from long swell waves from distant storms.

A.1.1 Qualitative Beach Composition Method.

"Red Beach" meets the criteria of a two-dimensional equilibrium beach. It is a small segment of a relatively long reach of straight beach. The surf is primarily due to local wind waves. Since the winds have been fairly constant, the beach has made a seasonal adjustment to a summer equilibrium profile. Therefore, a minimum of one sample is required under the break point in the surf zone. The longshore position of that sample point may be chosen based on operational consideration since the uniformity of the beach contour makes any point under the break point equivalent. The break point itself will maintain a nearly constant on-off shore position due to the small tidal range. Here the diver digs 6 inches below the bottom level and receives a handful of fine uniformly colored sand (fine sand beaches are common in arid coastal regions).



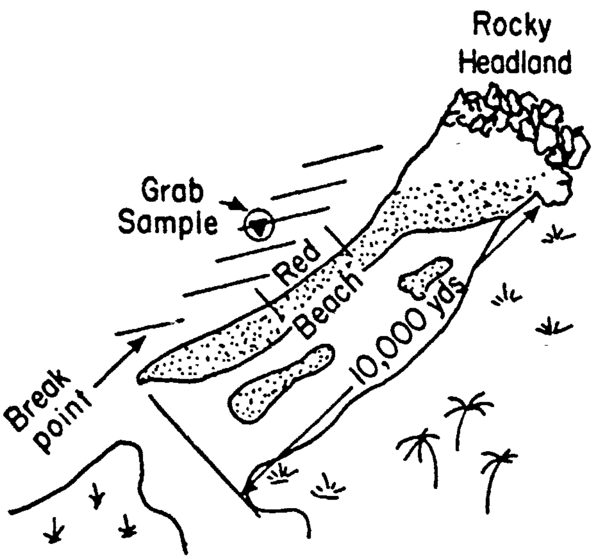


Figure A-1 Red Beach

Table A-1 shows that this is a "Group I" soil with a probable cone index range of 80 to 300 and a remolding index of 1.

Table A-1

Trafficability as a Function of Beach Composition When Wet

Group	Soils	Probable Cone Index Range	Probable Remolding Index Range	Probable Rating Cone Index Range	Remarks
I	Coarse-grained cohesionless sands and gravels.	80-300	1	80-300	Will support continuous wheeled traffic with low pressure tires. Moist sands good, dry sands fair.
II	Inorganic clays of high plasticity, fat clays.	55-165	0.75 to 1.35	65-140	Will usually support more than 50 cycles of wheeled vehicles. Traction may be difficult at times.
III	Clayey gravels, gravel-sand-clay mixtures, clayey sands, sand-clay mixtures, gravelly lean clays, sandy clays, inorganic clays of low to medium plasticity, lean clays, silty clays.	85-175	0.45 to 0.75	45-125	Will usually support limited traffic of wheeled vehicles. Traction will be difficult in most cases.
IV	Silty gravels, gravel-sand-silt mixtures, silty sands, sand-silt mixtures, inorganic silts and very fine sands, rock flour, silty or clayey fine sands or clayey silts with slight plasticity, inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts, organic silts and organic silty clays of low plasticity, organic clays of medium to high plasticity.	25-180	0.25 to 0.85	25-120	Will usually not support more than a single pass. Traction will be difficult in most cases. Applies to class I-III vehicles.

The rated cone index (RCI) is therfore

RCI = (80 - 300) x 1 = 80-300 psi

Table A-2 indicates that Red beach is trafficable to vehicles in categories 1 through 6, including all but rear wheel drive vehicles.

Table A-2
Classification of Vehicle Multi-Pass Trafficability

Category	RCI Range (PSI)	Vehicle Type
1	20 - 29	M29C weasel, M76 otter, snowmobile, all terrain cycles (ATC)
2	30 - 49	M-8A1 and M8A2 high-speed tractors, D-7 tractor and M-274 Mule
3	50 - 59	M151 series (4x4) Jeeps; M-4, M-6, M-8 (4x4) and (8x8) tractors; M-48 tank; M-101A1 Howitzer; LVT-P7 armored personnel carrier
4	60 - 69	M-60 tank, M-135 truck; LARC-5 (4x4) amphibious cargo carrier; M-34, M-49, M-50, M-59, M-60, M-108, M-109, M-275, M-561 (6x6) trucks; M-123A1, M-114 Howitzer
5	70 - 79	M-54 (6x6) truck; LARC-15 (4x4) amphibious cargo carrier; M-809, M-815, M-816, M-811 (6x6) trucks; XM198 Howitzer; M-1A1 155 mm gun
6	80 - 99	Rear-wheel drive trucks and trailed vehicles intended primarily for highway use, i.e., 4x2, 1/2 ton pick up trucks
7	100 or greater	Rear-wheel drive vehicles and others that generally are not expected to operate off roads, i.e., 4x2 5-ton dump truck

A.1.2 Quantitative Beach Composition Method.

The diver returns a soil grab sample taken under the break point to the insertion platform for subsequent size analysis. The hydrographic reconaissance determined a mean foreshore slope of about 1:50, or 2%, but a berm on the backshore has a local slope of 1:1.8.

On the insertion platform a teaspoon sized portion of this grab sample is poured into a 100 centimeter tall settling column filled with fresh water. A few of the largest grains reach the bottom of the settling column in 40 seconds, while the bulk of the sample falls in 50 seconds. Several other trials duplicated this result. Therefore, the average settling velocity is

$$W = \frac{100 \text{ cm}}{50 \text{ sec}} = 2 \text{ cm/sec}$$

Refering to Figure A-2, this settling velocity corresponds to a mean grain diameter of 200 microns.

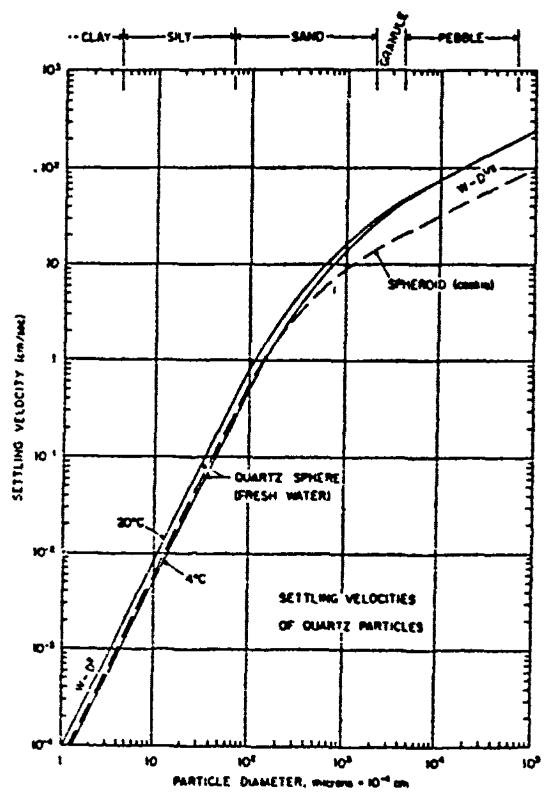


Figure A-2 Settling velocity for quartz sphere in dry air and fresh water

To utilize equations (2) or (3), we must convert to English units, as follows:

$$D = 200 \text{ microns} = 200 \times 10^{-4} \text{ cm} = 0.02 \text{ cm} = \frac{1 \text{ inch}}{2.54 \text{ cm}} = 0.0079 \text{ inches}$$

Furthermore, equation (2) requires the slopes, $\overline{B}$ and B_0, to be expressed in degrees. Expressing slopes as a ratio of 1:50 or 1:5 is equivalent to the tangent of the angle. Therefore, take the arctangent to calculate the slope angle:

$$\text{Mean foreshore slope } \overline{B} = \tan^{-1} \frac{1}{50} = 1.15^{\circ}$$

$$\text{Berm slope } B_0 = \tan^{-1} \frac{1}{1.8} = 29^{\circ}$$

because the mean grain size is 0.2 mm or 0.0079 inches, we use the following expression for equation (2) to calculate the wet cone index for the foreshore:

$$\text{Foreshore cone index} = \frac{2 \sin (32^{\circ} - 1.15^{\circ})}{\tan 32^{\circ} (1 + \cos 32^{\circ})} \left[10{,}240(0.0079) - \frac{0.158}{.0079} + \frac{0.0024}{(.0079)^2} \right]$$

$$= 88.2 \text{ psi (wet)}$$

Rated cone index: RCI = 88.2 x 1 = 88.2 psi (wet)

For the berm we calculate a wet cone index using the berm slope $B_0 = 29^{\circ}$, or

$$\text{Berm cone index} = \frac{2 \sin (32^{\circ} - 29^{\circ})}{\tan 32^{\circ}(1 + \cos 32^{\circ})} \left[(10{,}240)(0.0079) - \frac{0.158}{.0079} + \frac{0.0024}{(0.0079)^2} \right]$$

$$= 9.00 \text{ psi (wet)}$$

Berm rated cone index: RCI = 9.00 x 1 = 9.00 psi (wet)

Thus, the beach foreshore has a wet RCI of 99 psi while the steep berm has only a 9 psi value. Reading Table A-2, we find that the wet trafficability of the foreshore is fairly good, supporting all but rear wheel drive vehicles. However, we also note that all vehicles will have difficulty traversing the steep wave cut berm on the back shore, where locally the RCI is as low as 9 psi. If the berm cut is only a few feet high, tracked vehicles will be able to bridge this locally untrafficable region of the beach. Wheeled vehicles can be expected to loose traction on the drive wheels making contact with the berm cut.

The upper foreshore and the berm are probably dry other than at times of extreme tides and waves. Dry trafficability of fine sand is generally reduced relative to wet trafficability. In Table A-3, we note that a dry Group I type sandy soil retains only 46% of its wet strength.

Table A-3
Percentage of Saturated Wet Strength
As a Function of Moisture Content

	Water Content Within the 6 to 12 inch layer (inches)	Saturated Wet Strength (%)		
		Soil Group		
		I	II	III & IV
DRY	1.40	46	112	621
	1.40	46	111	621
	1.50	40	111	463
	1.60	26	109	352
	1.65	46	108	274
	1.70	55	105	208
	1.75	77	100	163
	1.80	91	100	126
SATURATED	1.85	100	100	100
	1.90	94	85	81
	1.95	87	77	65
	2.00	61	62	53
FLUIDIZED	2.05	47	56	42

Therefore, we estimate dry trafficability by

Dry foreshore: RCI = 88.2 x 0.46 = 40.6 psi

Dry berm: RCI = 9 x 0.46 = 4.1 psi

Thus, dry trafficability is considerably reduced in this fine sand, supporting multiple passes only for tracked vehicles having low contact pressure. However, these figures for dry RCIs are more representative of loose dry sand. Dry sand in place or natural beach have a packing and fabric structure that gives it additional strength.

A.1.3 SUROBS Method.

The hydrographic reconaissance measured breaker heights of between 0.7 and 0.8 meters at a period of 8 seconds. We calculate first the mean water depth in centimeters at the breakpoint as

$$h = \frac{5}{4}(75 \text{ cm}) = 93.75 \text{ cm}$$

We next calculate the threshold drag velocity in cm/sec for H_b = 75 cm, T = 8 seconds, and h = 94 cm, using equation (5):

$$U_\star = \left[\left(\frac{H_b}{2}\sqrt{g/h}\right)^2 + \left(\frac{2\pi H_b}{T}\right)^2\right]^{1/2} \times \frac{0.356\ T}{\sqrt{g\ h}} \qquad \text{Eq. (5)}$$

$$U_\star = \left[\left(\frac{75 \text{ cm}}{2}\sqrt{\frac{980\ (\text{cm/sec}^2)}{94 \text{ cm}}}\right)^2 + \left(\frac{2 \times \pi \times 75}{8}\right)^2\right]^{1/2} \times \frac{0.356 \times 8}{\sqrt{98^0 \times 94}}$$

$$= 1.26 \text{ cm/sec}$$

We refer next to Figure A-3 and find in the plot labeled "B" that a threshold drag velocity of $U_{\star} = 1.26$ cm/sec corresponds to a mean grain size of 0.2 to 0.3 mm. (Note when reading these curves that they are plotted on a log-log scale.)

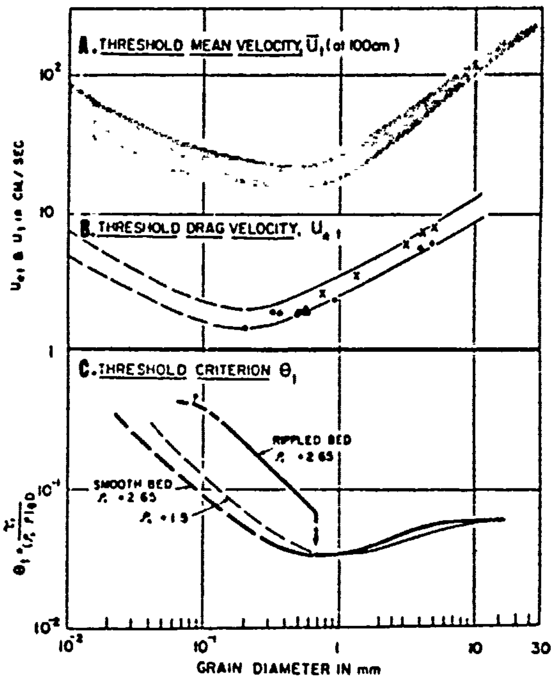


Figure A-2 Dependence of grain size on A) Threshold velocity, B) Friction velocity, and C) Shields parameter (from Reference (14))

Convert the mean grain size to inches:

$$D = 0.3 \text{ mm} = \frac{0.03 \text{ cm}}{2.54 \text{ cm/inch}} = 0.0118 \text{ inches,}$$

and calculate the wet cone index from equation (2) as before. We repeat the calculation here for 0.3 mm size sand:

Wet cone index of foreshore

$$= \frac{2 \sin (32^\circ - 1.15^\circ)}{\tan 32^\circ (1 + \cos 32^\circ)} \left[10{,}240 \, (0.0118) - \frac{0.158}{0.0118} + \frac{0.0024}{(0.0118)^2} \right] = 110.7 \text{ psi}$$

Wet RCI of foreshore = 110.7 x 1 = 110.7 psi

To calculate the dry trafficability, we refer to Table A-3 and find that a dry sample of a Group I cohesionless soil has only 46% of its saturated wet strength. Therefore, we find:

Dry RCI of foreshore = 110.7 psi x 0.46 = 50.9 psi

Thus, the SUROBS method gives roughly equivalent answers to the quantitative composition method. The difference is primarily the method in selecting the mean grain size. The SUROBS method of determining mean grain size involves uncertainties due to the scatter of data in Figure A-2.

A.1.4 Aerial Photographic Method.

The tidal range is only 0.5 feet and is inadequate to accurately determine foreshore slopes or foreshore mean-sea-level widths. However, we note that the foreshore slope of 1.15° corresponds to a mean grain size of 0.20 to 0.22 mm, according to Figure 3-10. Therefore, a repeat of calculations for cone indices using equation (2) will give the same results as those found in the previous computations or SUROBS methods.

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